Decision-Support Framework for Integrated Asset Management of Major Municipal Infrastructure

Khaled Farouk Shahata

A Thesis

In the Department

Of

Building, Civil & Environmental Engineering

Presented in Partial Fulfillment of the Requirements

For the Degree of Doctor of Philosophy (Building Engineering) at

Concordia University

Montreal, Quebec, Canada

April 2013

CONCORDIA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

This is to certify that the thesis prepared

By: Khaled Farouk Shahata

Entitled: *Decision-Support Framework* for Integrated Asset Management of Major Municipal Infrastructure

and submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY (Building Engineering)

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

______________________________ Chair
Dr. I. Hassan

______________________________ External Examiner
Dr. J. H. Rankin

______________________________ External to Program
Dr. M. Y. Chen

______________________________ Examiner
Dr. Z. Zhu

______________________________ Examiner
Dr. A. Bagchi

______________________________ Thesis Supervisor
Dr. T. Zayed

Approved by ____
Dr. M. Elektorowicz, Graduate Program Director

April 24, 2012

____
Dr. Robin A.L. Drew, Dean
Faculty of Engineering & Computer Science

ABSTRACT

Decision-Support Framework for Integrated Asset Management of Major Municipal Infrastructure

Khaled Farouk Shahata, PhD, P.Eng

Concordia University, 2013

"Canada's municipal infrastructure is at risk." This was the key finding of Canada's first municipal infrastructure report card. Given the current state of risk for Canadian infrastructure, municipalities face challenging decisions for planning the integrated repair/renewal of road, water and sewer networks. Decision-making surrounding the assets in these networks requires data collection, analysis, the identification of decision variables and undertaking optimized decision-making processes. Currently there is a lack of tools available to simplify the decision making process for stakeholders.

The research objective is to establish a methodology and framework that facilitates decision-making processes used during corridor rehabilitation project planning. The proposed framework consists of three main models: (1) Risk assessment, (2) Performance evaluation and (3) Integrated decision support system (IDSS).

The risk model was developed using a mixed Delphi-Analytical Hierarchy Process approach. The impacts of four main consequences of failure with eighteen sub factors were considered. Road, water and sewer networks indices were amalgamated and grouped into an overall integrated risk index using *K-means Clustering technique*. The performance model considers nine factors that represent the asset performance. These factors were mapped using fuzzy logic technique to a Customer Driven Performance Measure (CDPM) index. The IDSS framework allows the setting of priorities for integrated corridor rehabilitation and implementing optimization via Integer Programming. Finally, these models were applied in a prototype tool using Visual Basic built on Microsoft Access, Excel and GIS platforms. A series of workshop interviews were conducted with various municipalities to collect the necessary information. Data provided by the City of Guelph was used in a case study in order to demonstrate the model features.

Results show that Pipe/road size and accessibility factors had the highest impact on the integrated risk index. The road roughness rating and watermain breaks results show the highest impact on the CDPM index. Optimization outcomes demonstrated that corridor rehabilitation alternatives resulted in a 'maximum risk reduced per dollar spent'. The developed models can be used by researchers and practitioners (municipal engineers and consultants) in order to prioritize corridor rehabilitation projects thereby easing the challenge faced by stakeholders regarding the future of municipal infrastructure.

Dedication

To My Parents; Farouk Shahata and Mahaseen Gouda

and

My Family; Basma Mohamed, Jumana and Arwa

ACKNOWLEDGEMENT

First I am extremely thankful to **ALLAH** for all His guidance and blessings that enabled me to accomplish this work. I ask **ALLAH** to accept this work from me, and to make it sincere and solely for His sake.

I would like to thank my supervisor, Professor Tarek Zayed, for his help, valuable advice and support throughout my studies at Concordia University as well as aiding me to find my first job in the construction management industry. I have learned a lot from him and it was a great honor to work under his supervision.

I am really thankful to my wife, Basma Mohamed, for all her love, patience, and understanding particularly during her tough pregnancy stages. She has been extremely supportive, cooperative, and my source of strength and inspiration. I also owe a lot to my little angles Jumana and Arwa for all the time I took away from them to work on this research.

I am so grateful to my beloved parents, Professor Farouk Shahata and Mahaseen Gouda, for all their infinite love, support and cooperation throughout my life. I wouldn't have been able to accomplish my goals without their on-going encouragement and prayers. I would also like to thank my sister, Dalia, and brothers, Ahmed & Mohamed, for their support and prayers.

Moreover, I would like to express my gratitude to all the municipal and consultant associates who facilitated my research through positive participation, knowledge, careful revisions and criticism thereby offering sound professional advice and welcome friendship.

I would also like to express my special gratitude to my colleague and life time friend Dr. Ahmed Eweda for his endless encouragement and support. Finally, I am indebted to my Professors, friends, and colleagues in the Construction lab at Concordia University who have helped make my learning an enjoyable and stimulating experience.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

AASHTO	American Association Of State Highway And Transportation Officials
AHP	Analytical Hierarchy Process
CCTV	Closed Circuit Television
CDPM	Customer/Client Driven Performance Measure
COF	Consequence Of Failure
ESL	Estimated Service Life
FL	Fuzzy Logic
GASB	Governmental Accounting Standards Board
GIS	Geographic Information System
ICG	Internal Condition Grade
IDSS	Integrated Decision Support System
IP	Integer Programming
IRA	Integrated Risk Assessment
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LOS	Level Of Service
MMS	Maintenance Management Systems
NAPPI	North American Association Of Pipeline Inspectors
NASSCO	National Association Of Sewer Service Companies
NPV	Net Present Value
O&M	Operation And Maintenance
ODM	Optimized Decision-Making
PMS	Pavement Management Systems
POF	Probability Of Failure
PQI	Pavement Quality Index
PSAB	Public Sector Accounting Board
QA/QC	Quality Assurance /Quality Control
R/W/S	Road/Water/Sewer Assets
RCI	Riding Comfort Index
RI	Risk Index
RSL	Remaining Service Life
SDI	Surface Distress Index
SPG	Structural Performance Grade
TCA	Tangible Capital Assets
VBA	Visual Basic Applications
WP	Water Pressure
WQ	Water Quality
WRc	Water Research Centre

CHAPTER 1: INTRODUCTION

1.1 Problem Statement

Canadian municipalities face challenging decisions planning the repair/renewal of road, water and wastewater networks. Part of the challenge involves the integration of roads, water and wastewater where the infrastructure shares the same space, the right-of-way. Water supply and sewer systems, in Canada, have reached a point where maintenance and renewal is essential. The first Canadian Infrastructure Report Card was recently published which assessed the condition of these three key elements of infrastructure. The Report's data was based on survey responses from one hundred and twenty three (123) Canadian municipalities. The Canadian Construction Association (CCA), Canadian Public Works Association (CPWA), Canadian Society for Civil Engineering (CSCE) and Federation of Canadian Municipalities (FCM) conducted the survey which was published at the end of 2012. Findings show that about 30% of municipal infrastructure is assessed between fair and very poor. Many municipalities do not practice what is currently encouraged by upper tier governments regarding formal processes for the asset management of municipal infrastructure. The replacement cost of municipal assets is significant and estimated at $171.8 billion, nationally (CCA et al. 2012). An earlier survey conducted by the Canadian National Research Council, indicated that rehabilitation of municipal water systems would cost $28 billion from 1997 to 2012 (NRC, 2004). InfraGuide (2003b) stated that 85% of Canadian roads need repair and there was no clear integrated comprehensive long-term planning for municipal infrastructure facilities. Infraguide says that this problem is reflected by a growing budget deficit in most municipalities. Municipalities can suffer from lack of collaboration and communication among different internal and external groups, resulting in unnecessary restoration work, duplication of effort, etc. The potential benefits that can be realized through an integrated approach to infrastructure rehabilitation and management practices remain available for exploitation by Canada's municipalities. Integrated decision making for road, water and wastewater infrastructure is a key component in the determination of when to repair or replace any of these assets and can allow to realizing the many benefits of asset management.

1.1.1 The Need for Integration Planning

Industry concerns in Canada are the driving factor behind the research developed within this dissertation. It was found that lack of adequate funding has placed significant pressure on municipalities to improve the effectiveness with which they manage their infrastructure inventory. Increased effectiveness can be achieved through adoption of more efficient, sustainable, and proactive asset management strategies. Traditionally a municipality will describe a project as a road, sewer or water project. Functionally, all three can take place in the same right-of way often at the same time. However, they are rarely considered together in a fully integrated decision-making process. Budgets are often built by the service or department and not by the impact zone. Municipal experts mentioned that the most common practice is to tag the smaller job into the largest project moving forward. Development of a useful and user-friendly tool can help decision makers as they strive towards optimum replacement decisions where municipalities undertake multiple uses within a specified right - of - way.

1.2 Research Hypothesis

The hypothesis guiding the completion of this research is as follows: The integration of decision-making process for road, watermain and sewermain infrastructure can reduce the asset risk exposure and advocate the use of various corridor rehabilitation alternatives. The hypothesis will be studied and verified through the integration of risk, performance, optimization process and implementation of an integrated decision support system.

1.3 Research Objectives

The objective of this research study is to establish a methodology that will facilitate decision-making processes used during corridor rehabilitation projects planning that include road, water and wastewater infrastructure assets. In order to fulfill this objective the following sub objectives were determined:

1- Identify and study the various factors that contribute to assessing municipal infrastructure risks and quantifying client/customer driven infrastructure performance measures.
2- Establish an integrated risk assessment model and client driven performance index for municipal infrastructure that can be applied specifically to projects involving roads, water and wastewater.

3- Develop an optimized capital investment plan and integrated decision support system (IDSS) for corridor rehabilitation projects.

4- Develop a prototype tool for the IDSS.

1.4 Methodology

The research plan set to achieve the objectives of this dissertation consists of three main phases. These phases are defined as follows:

1.4.1 Review of Current Asset Management Practices

1- Review the existing state-of-the-art, to achieve a thorough understanding of the area of interest (asset management practices), and to analyze the approaches taken during decision-making for the corridor rehabilitation of the road, water and wastewater network.

2- Review some of the available commercial software packages on asset / maintenance management by studying their operating characteristics and functionalities.

3- Conduct interviews and discussions with asset management professionals.

1.4.2 Develop Framework and Model

The development phase of the integrated corridor rehabilitation includes:

1- Collect and analyze data and data gaps: preparing questionnaires, conducting interviews, and accessing the GIS geodatabase, maintenance records, and various consultant reports for the City of Guelph, Ontario, Canada.

2- Develop an assessment process for risks related to combined roads / water / sewer infrastructure projects:

   a. *Identification of Risk Factors*

   b. *Consequence of Failure*: Design a hierarchy of the major criteria that contribute to consequence of failure for each Road / Water / Sewer (R/W/S) asset. Determine the weight of each factor using the Analytical Hierarchy Process (AHP).

   c. *Probability of Failure*: Build on the existing condition rating and deterioration models available in literature; adopt a suitable model for road, sewer and water infrastructure assets.

   d. As an outcome of this model, develop an integrated overall Risk Index for road, sewer, and water assets. Amalgamate and group these indices into an overall integrated Segment Risk Index using K-means Clustering (K-means).

3- Develop integrated performance evaluations for each asset class: First, identify key performance indicators for each asset class. Second, establish and measure performance. Third, link the key performance indicators to a desired level of service using fuzzy logic. The outcome of this model is an integrated overall Client Driven Performance Index for road, sewer and water assets.

4- Develop a decision support model (prioritization using optimization): this task utilizes the available replacement / rehabilitation actions, sets priorities for integrated corridor rehabilitation, implements optimization of repair / renewal costs and defines the best replacement interval via Integer Programming (IP).

1.4.3 Prototype Development and Implementation.

Prototype development and implementation involves definition of architecture and user interfaces for the integrated system. The prototype is expected to be an add-on to ESRI ArcGIS software. The integrated prototype application will be implemented as a set of modules; each module addresses one stage of the integrated planning process. This prototype will require the amalgamation of MS-Access, MS-Excel, Oracle, Palisade Decision Tools Suite 5.5, and ESRI ArcGIS software.

1.5 Dissertation Organization

1.5.1 Chapter Two

This chapter discusses the current environment for asset management systems in terms of modeling and hierarchy, condition assessment, performance evaluation and deterioration modeling, risk assessment, rehabilitation and replacement for major infrastructure. A variety of prioritization frameworks are examined. Finally the chapter compares popular optimization techniques used for road, sewer and water assets infrastructure assets.

1.5.2 Chapter Three

This chapter discusses the research methodology and conclusions regarding the Current Asset Management Practices Review, the Framework and

Model development, and introduces the Prototype Development and Implementation.

1.5.3 Chapter Four

This chapter highlights the data collected for the case study used to test the model. The results of a sensitivity analysis of data gaps are presented. This chapter also addresses the workshop and questionnaire feedback that contributed to this research.

1.5.4 Chapter Five

This chapter covers the integrated (road, water and sewer) asset management model development process. This chapter is divided into four main sections: 1) integrated risk assessment, 2) integrated performance evaluation, 3) development of the decision support optimization model, and 4) prototype development and implementation. Each section contributes to the model development in which all assessment attributes are identified in the decision support framework. The proposed model methodology based on GIS technology is applied to the case study. A step-by-step procedure for assessing a sub-network by defining the road, sewer, and water assets parameters is explained and discussed.

1.5.5 Chapter six

This chapter covers the Model implementation procedures, data processing, assumptions, results and analysis in which a case study is demonstrated, processed and implemented as a proof of concept. Validation and evaluation of the models was conducted via sensitivity analysis and a comparison of the model results against the results expected by the City's asset managers. Moreover the model and the automated tool were validated by experts working in these fields. The chapter concludes with the implementation challenges and key lessons learned through the development and implementation process.

1.5.6 Chapter seven

This final chapter reports the findings of this dissertation including the research conclusions, limitations, and contributions. Potential areas for future research are discussed. Final recommendations are shared.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Public and private agencies have always tried to maintain their infrastructure assets in good and serviceable condition at a minimum cost; therefore, they practiced infrastructure management. However, as most of the nation's infrastructure systems reached maturity and the demands placed on them started to rapidly increase in the mid- 1960s, infrastructure agencies started to focus on a systems approach for infrastructure management. This process has lead to today's Asset Management Concept. The process started with the development of Pavement Management Systems (PMS), continued with Bridge Management Systems (BMS) and Infrastructure Management Systems (IMS), and has recently evolved into Asset Management (Ferreira and Flintsch, 2004).

This chapter summarizes Literature review of various Asset Management best practices. The first section defines Asset Management of municipal infrastructure to establish a common understanding through the dissertation, followed by an overview of existing Asset Management best practices in terms of modeling and hierarchy, risk analysis, condition assessment, and performance evaluation. It also summarizes a variety of prioritization framework and concludes with a comparison of optimization techniques used for R/W/S infrastructure assets.

2.2 What is Asset Management of Municipal Infrastructure?

2.2.1 Definition of Asset Management

"The combination of management, financial, economic, engineering, and operational and other practices applied to physical assets with the objective of providing the required level of service in the most cost-effective manner." (InfraGuide, 2005)

Asset management has been described as *"a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making. Thus asset management provides a framework for handling both short and long range planning"* (Transportation Association of Canada, 1999).

Transportation asset management is a set of guiding principles and best practice methods for making informed transportation resource allocation decisions, and improving accountability for these decisions. The Asset Management Guide recently adopted by AASHTO defines asset management as (AASHTO, 2002):

"... a strategic approach to managing transportation infrastructure. It focuses on...business processes for resource allocation and utilization with the objective of better decision-making based upon quality information and well-defined objectives."

The following definition suits many organizations managing municipal infrastructure and it can be adopted or adapted to meet their internal needs (Vanier and Rahman, 2004b) and was adopted for this research:

“ Asset management is a business process and decision-support framework that: (1) covers the extended service life of an asset, (2) draws from engineering as well as economics, and (3) considers a diverse range of assets.”

Asset management is neither a new term in the industry, nor a new process for municipalities. The term was first used in the construction context two decades ago to describe the life cycle of physical assets (Burns, 1990). In addition, asset management is what public works officials have been doing for centuries.

2.2.2 Definition of Municipal Infrastructure

The Canadian Oxford Dictionary defines “infrastructure” as “the basic structural foundation of a society or enterprise; roads, bridges, sewers, etc. regarded as a country's economic foundation.” Many organizations are also using the term *civil infrastructure systems* (CIS) to describe this type of built asset to distinguish it from other forms of infrastructure such as computer networks (Vanier and Rahman, 2004b). Municipal infrastructure, a distinct portion of civil infrastructure, includes those assets managed by municipalities. These typically include, but are not restricted to, the following classes of assets:

Linear Assets: Linear assets are assets generally constructed or arranged in a continuous and connected network. “Infrastructure – Linear assets” includes:

- Surface systems such as roads, sidewalks, bridges, drainage ditches, and street lights; and
- Underground systems such as water distribution pipe systems, wastewater collection pipe systems, manholes, catch basins, and storm drainage collection systems and tunnels

Facilities: all structures that provide shelter from the elements, includes general buildings that are owned by the municipality. Examples include community facilities (e.g. arenas, community centers, parks and recreation, libraries, etc…) and corporate facilities (administrative buildings, fire halls, yards, salt domes, etc.…)

Linear or ‘infrastructure’ assets are the largest stock of assets in terms of value. For example, the City of Winnipeg’s Consolidated Financial Statement that was prepared in accordance with PSAB PS-3150 (PSAB and CICA, 2007) reporting requirements accounted 80% of the City’s Tangible Capital Assets (TCA) fall within the ‘infrastructure’ category (City of Winnipeg, 2006).

2.3 Asset Management Best Practices

There are two main streams in modeling infrastructure: first, the project level or referred to as “bottom-up approach”, in which each element in the hierarchy at the bottom level is assumed to be one project and has a different renewal plan. Second, the network level or referred to as “Top-down approach”, in which all assets that share the same circumstance are assumed to be one element. You estimate the renewal cost for a group of assets by using their replacement cost and estimated service life. The presented research introduces an intermediate approach between the two levels outlined above by utilizing a segment level approach in the modeling of deterioration, condition, and risk; then employs a network level approach for optimization of corridor rehabilitation. The following sections outline a number of international and national activities related to asset management.

The National Guide to Sustainable Municipal Infrastructure (NGSMI) is funded under the Infrastructure Canada Program (ICP) and managed by the Federation of Canadian Municipalities (FCM) in partnership with the National Research Council of Canada (NRC). The *Guide* provides a roadmap to the best available solutions (i.e. *best practices*) for addressing municipal infrastructure issues (InfraGuide, 2005). It also serves as a focal point for the Canada-wide network of practitioners, researchers, and municipal governments focused on infrastructure operations and maintenance. The *Guide* addresses six target areas: environment protocols, municipal roads and sidewalks, decision-making and investment planning, transit, potable water (production and distribution), and storm and wastewater.

Figure 2-1 shows asset management planning framework as described within the InfraGuide (2005) report. Asset management is premised on the following component requirements: asset value, life cycle management, sustainability, integration of technical and financial plans, risk assessment, performance measurement, as well as high-level and detailed plans.

The Municipal Infrastructure Investment Planning project (Vanier and Rahman, 2004a) investigates the actual and sustainable "Level of Investment" expenditures for maintenance of municipal infrastructure, the extent of asset management in practice today, and the state of Canada's municipal infrastructure assets. Vanier and Rahman stated that municipal infrastructure managers were able to provide reliable answers to the first three asset management "what's": what do you own, what is it worth and what the deferred maintenance is. However, regarding the last three "what's", researchers and practitioners should develop and standardize tools and techniques to determine asset condition, to predict remaining service life and to prioritize maintenance and capital renewal.

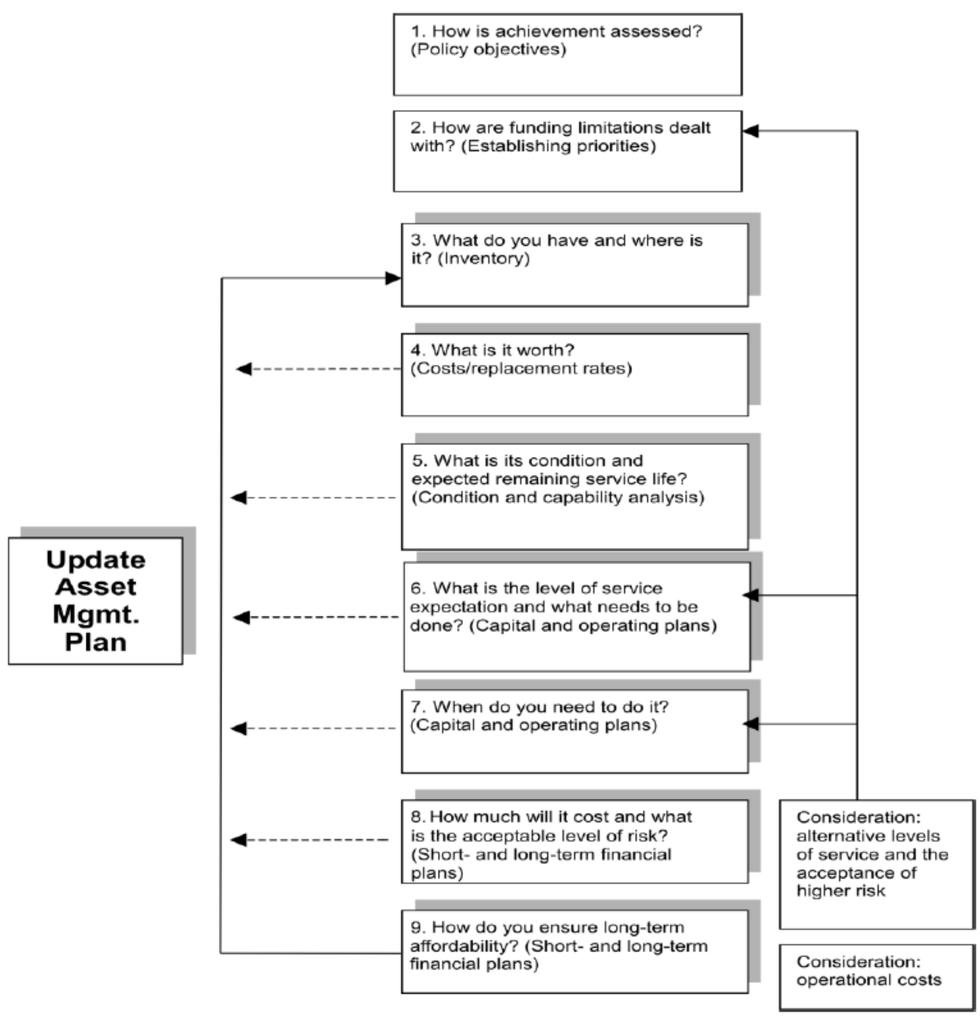


Figure 2-1 Asset Management Planning Framework (adopted from InfraGuide, 2005)

The Transportation Association of Canada (Transportation Association of Canada, 1999) has published a *Primer on Highway Asset Management* defining asset management, identifying its benefits, listing the components of an asset management system, discussing critical success factors, and itemizing a seven-step implementation plan. The potential for partnering and benefits are also illustrated in the report.

The Institute of Public Works Engineering Australia (formerly the Institute of Municipal Engineers Australia-IMEA) and the New Zealand National Asset Management Steering (NAMS) Group have jointly developed an International Infrastructure Management Manual (IIMM, 2006 and IIMM, 2011). This manual is divided into five sections: introduction, implementing asset management, implementing techniques, asset management information systems, and country specific information. The manual defines the basic integrated asset management principles and works through to practical steps for implementing advanced asset management. The manual set details of asset management standards, guidelines, techniques and references together with examples of key asset management activities such as: developing and consulting on service levels, optimized decision-making, maintenance planning, demand forecasting, and risk management methods. It provides principles and processes of asset management implementation guidelines, shows how to evaluate and implement information systems to support good asset management planning and decision-making.

Federal Highway Administration (FHWA), US Department of Transportation has published a number of primers on asset management (FHWA, 1999), life cycle cost analysis (FHWA, 2002) , GASB 34 and data integration. FHWA (2002) has also developed software and user guides for two applications: Pavement Life Cycle Cost Analysis (LCCA) and Highway Economic Requirements System/State Level (HERS/ST). LCCA is an economic tool linked to project level decision-making. The tool applies probabilistic and deterministic approaches to find the lowest cost investment option that obtains the maximum return on pavement maintenance funding.

In other words, Asset managers are faced with many challenges regarding when and how to inspect, maintain, repair and replace a diverse set of existing infrastructure assets cost effectively. There are a few tools available in the form of standards, guidelines, technical literature, or best practices to assist them in their decision-making. However, it is extremely difficult for organizations to evaluate all these solutions for suitability that meets their needs, as it is not specific to their needs / issues. It is recommended that a specific decision support framework for implementing these solutions be developed.

2.3.1 Integration of Infrastructure Management

Efficient management of municipal infrastructure systems is currently more focused on the overall integrated multi-disciplinary aspects of Infrastructure Management processes. The development and deployment of integrated infrastructure management systems is currently more of a necessity to maintain our infrastructure assets. Integrated infrastructure management would facilitate information flow across various disciplines and activities, which in return would improve the availability, reliability, and consistency of infrastructure information, resulting in timely and more efficient decisions. The need to adopt an integrated approach to infrastructure management is widely recognized in industry and academia (InfraGuide (2003a); Halfawy et al. (2002); Grigg (1999) and Lemer (1998)).

Throughout the last two decades, municipalities have made significant investments in implementing software tools that focus on infrastructure management processes (Vanier (2001) and Halfawy et al. (2006)). The majority of the software tools were developed to function as stand-alone systems, and many have limited or no capability for sharing or exchanging information with other tools. Halfawy et al. (2006) reviewed commercial asset management systems in Canada; this paper aims to provide asset managers with an objective review of existing systems and technologies, and to identify a number of considerations that need to be addressed in the process of selecting an asset management system. It also highlights areas where further research and development are needed in order to extend the scope and capabilities of existing systems.

The InfraGuide report suggested a systematic integration approach for the renewal of municipal road, sewer and water systems (InfraGuide, 2003a). This approach consists of five tasks as shown in Figure 2-2. The approach is based on collecting data inventories, investigations, condition assessment and performance evaluation. This evaluation can be completed independently for road, sewer and water systems. It should be noted that critical infrastructure assets should be dealt with separately from the non-critical assets throughout all phases of the process. Finally, the approach concludes with task five; developing a sound renewal plan, which include economic analysis, coordination with growth needs regulations, and risk management. The report set a high-level framework for municipalities to adopt which will standardize procedures and integration of asset management initiatives. It is recommended for municipalities and government officials to join forces to enforce and standardize these practices among all municipalities.

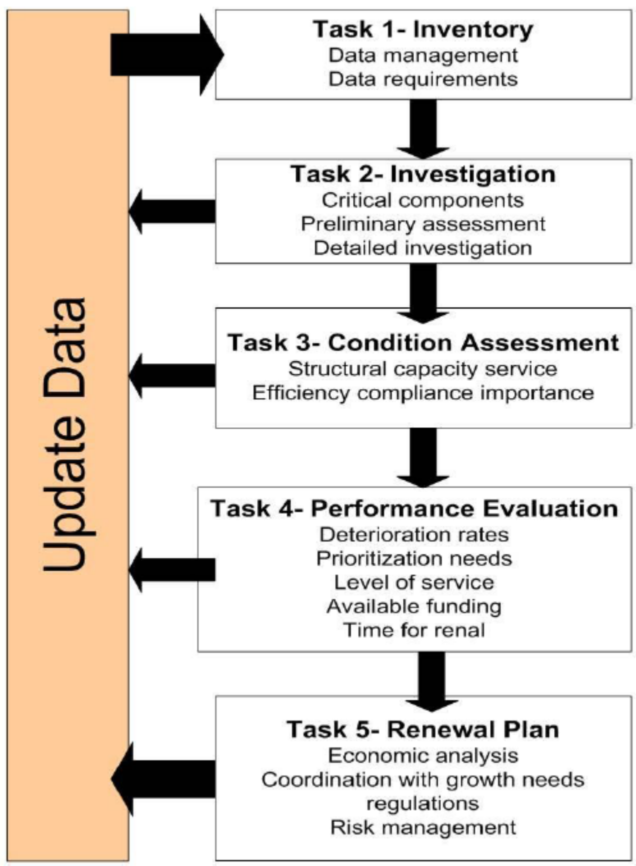


Figure 2-2 Integrated Approach to Assessment and Evaluation (adopted from InfraGuide, 2003a)

Although significant research efforts have focused on developing techniques and models to support individual infrastructure management processes, the development of integrated models has received little attention in the literature (Halfawy, 2008). Ganeshan et al. (2001) developed a collaborative and integrated environment (CITYWORK) to support maintenance management of civil infrastructure systems. That study emphasized the need for integrated infrastructure management systems, however, it pointed out, “it will require significant investments in time, effort, and resources to get these environments created and customized.” Shen and Spainhour (2001) emphasized that “the tools and methodologies for infrastructure life-cycle management should integrate environmental, economic, and technical issues into a *total solution*.”

Several researchers have described the processes needed to implement municipal infrastructure management programs. Lemer (1998) described these processes as being comprised of two main sets of issues: (a) asset identification, appraisal, and valuation; and (b) asset deployment, utilization, exchange, and reinvestment. InfraGuide (2003a) identifies five main areas of infrastructure asset management for integration of municipal infrastructure systems. These areas included: asset inventory, investigation, condition assessment, performance evaluation, and renewal plans development. Although these high-level definitions provided insight into the main processes, they did not provide sufficient details about their organization, interrelationships, and integration information requirements. Therefore, formalizing a more-detailed business process model is needed.

There are several applications intended to develop a municipal infrastructure management systems (Lee and Deighton (1995); Quintero et al. (2003); Ferreira and Duarte (2005); and Halfawy (2008)). Municipalities have discovered that they possess many separate databases and that each one contributes significantly to the mission of the infrastructures department that owns and maintains it. They have recognized the need to combine and to explore relationships among various data resources, and, when possible, to make them available to other organizations and the public. Currently there are no accepted standards or practices for dealing with spatial issues, which then originate a great diversity.

Ferreira and Duarte (2005) proposed base liner referencing system (LRS) for an Integrated Infrastructure Management System is an attempt to provide a common referencing platform in which different data types can be represented spatially in a network structure in a standardized manner. The base LRS is intended to be the nucleus of the relational database and the GIS. Ferreria only examined the road network using his proposed technique; also failing to introduce optimization in his proposed model.

On the other hand, Halfawy (2008) has proposed a detailed framework to address a number of issues, including: asset life-cycle data modeling, sharing, and management, systematization of municipal processes, and integration of disparate software tools in a flexible and modular architecture. Halfway (2008) emphasizes data modeling and integration of software tools, rather than the details of individual integration processes (e.g. risk assessment, renewal planning, and optimization). Halfway did not identify decision trees and/or business barriers between various municipal departments. Therefore, formalizing a more-detailed integrated business process model is considered necessary.

Pradhan et al. (2007) proposed a three-tiered architecture that separates the functionality between data, business logic, and applications tiers, to support the development of integrated infrastructure data repositories and decision support systems for disaster management. Pradhan's focus was only limited to the data architecture and did not proceed into the evaluation or implementation of an integrated decision support system.

More recently, Islam and Moselhi (2012) presented a computational model for establishing the interdependence among municipal assets. Their proposed model offers a methodology to systematically group assets based on their location and geometry to support corridor rehabilitation of municipal assets using GIS platform. This study presented an in-depth GIS spatial analysis that can be used as a starting point to prepare data in order to support integration of decision making for collocated assets. Additionally, Islam and Moselhi (2011) proposed a three-stage framework for corridor rehabilitation: network analysis, asset interdependence and integrated planning. The integrated planning module uses a threshold-based computational model for integrated asset planning for water, sewer and road assets (Islam and Moselhi, 2011).

In conclusion, any integrated asset management program should support long-term planning, considering that municipal infrastructure assets have life-cycles that may extend from 10 years, as in roads, to 100 years, as in watermains. That extended time horizon requires consideration and/or development of life-cycle cost, deterioration models and service-life forecasting models, coordination and integration of infrastructure needs (Moselhi, 2005). Danylo and Lemer (1998) described the main role of an infrastructure asset management system as "*an integrator, a system that can interact with and interpret the output coming from many dissimilar systems*." Shen and Spainhour (2001) emphasized that "*the tools and methodologies for infrastructure life-cycle management should integrate environmental, economic, and technical issues into a total solution*."

2.4 Risk Assessment

The Risk concept is a crucial first step in determining the management approach for many infrastructure assets. Low-risk road segment, sewer, and/or watermains, where failure can be addressed through the course of normal operations, should be treated differently than high-risk 'critical' road segment, sewer, and/or watermains, whose failure strains operations and/or results in considerable economic, environmental and social ramifications. Risk is defined by (InfraGuide, 2006) as the combination of the probability and impact severity of a particular circumstance that negatively affects the ability of infrastructure assets to meet the objectives of the municipality. Moreover, the probability is defined as the likelihood of an event occurring.

Effective Asset Management relies on the principals of risk management to plan and prioritize work activities. In this context, "Risk Exposure" is defined as the product of the probability and consequences of asset failure. Understanding the relative risk exposure for a given set of assets allows us to identify those assets most susceptible to failure and consequently target our investments to provide the greatest benefit.

A typical Risk Model combines an asset's attributes and characteristics of its surrounding environment (e.g. location relative to facilities or other infrastructure) to rate its Consequences of Failure. Basic models rely on three or four variables to calculate the relative 'cost' associated with the repair and reinstatement of an asset after failure. More complex models use multiple variables and weighting factors to rate several impacts (e.g. economic, operational, environmental, and social) either combined or individually. As with rating systems, the complexity of a Risk Model should reflect the potential risk exposure for a given group of assets, and the level of information needed to support effective planning and prioritization.

Consequences of failure imply a loss of some kind. Losses can be quantified in terms of damaged property, vehicles, cost of service interruption & lost product, clean-up cost, etc. The consequences of failure are categorized into two groups: direct and indirect consequences as shown in Table 2-1 (Muhlbauer (2004) and Bhave (2003)).

Table 2-1 Consequences of Failure Categories

Direct consequences	**Indirect consequences**
• Property damages • Damages to human health • Environmental damages • Loss of product • Repair costs • Cleanup and remediation costs	• Litigation and contract violations, • Customer dissatisfaction, • Political reactions, • Loss of market share, and • Government fines and penalties.

Even though identifying probability of failure for infrastructure assets through deterioration models has attracted attention of several researchers, determining the consequences of failure and incorporating this information to prioritize assets has not been fully examined.

2.4.1 Risk Assessment for Water Assets

Many researchers investigated risk modeling for water infrastructure. In their efforts to assess the risk or the probability of pipeline failure, researchers have used a broad variety of techniques. These techniques vary in scope and complexity, such as applying fuzzy logic to quantify the probability of failure and / or condition (Fares (2008), Fares and Zayed (2009) Marshall et al. (2005); Kleiner et al. (2006); and Rajani et al. (2006)). Kleiner et al. (2004) represented consequences of failure by using fuzzy sets and combined the consequences of failure with possibility of failure in order to determine the risk of failure by using a fuzzy-rule based system. Other researchers have used Monte Carlo simulation (Sadiq et al. (2004), also the analytical hierarchy process (Bandyopadhyay et al. (1997), Al Barqawi (2006) and Al Barqawi and Zayed (2008)), and multi-criteria decision making (Yan and Vairavamoorthy, 2003). Most of these studies have focused on the probability of failure with a little focus on the consequence of failure.

Fares and Zayed (2009) developed a risk model for watermain failure, which evaluates the risk associated with each pipeline in the network. This model considers four main factors: environmental, physical, operational, and post-failure factors (consequences of failure) and fifteen sub-factors which represent the main factors as shown in Figure 2-3. Hierarchical fuzzy expert system technique is used to process the input data, model the effect of risk factors, and generate the risk of failure index of each watermain.

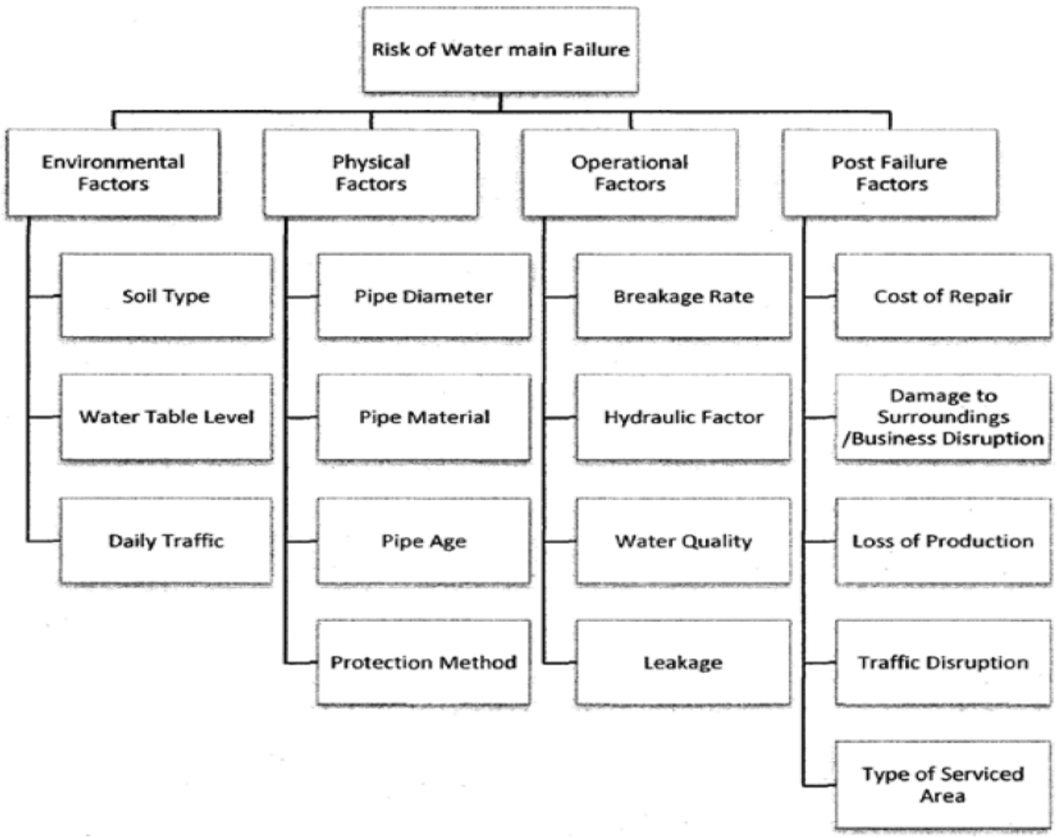


Figure 2-3 Risk Factors of Watermain Failure (Fares and Zayed, 2008)

2.4.2 Risk Assessment for Wastewater Assets

WRC (2001) manuals suggest that substantial savings can be made by preventing a few expensive failures and the identification of these may be achieved by categorization of sewers. Category "A" sewers are those where failures would be most expensive, "C" where they would be relatively cheap and "B", an intermediate category. WRC procedures require exercising of engineering judgment at each step. In the WRC manual, engineering and traffic delay costs are highlighted by a system of cost factors, which indicate the relative cost consequences in the event of failure. The City of Toronto developed a risk model for waste water assets using WRC approach (Shahata, 2008).

City West Water's Asset Criticality Risk Model (ACRM) has been developed using the approach detailed in the AS/NZS4360 (2004) Risk Management standard. The system uses a matrix to categorize each asset into one of the five by five likelihood of failure and consequence of failure scenarios. City West Water has differentiated the consequence of failure of assets into social, environmental and economic impacts to appropriately differentiate the drivers for renewal or management of the assets that may apply in different locations. Generally the higher consequence rating is used in combination with the applied condition grade to determine the highest level of risk for the pipeline. The criteria applied to assess the consequence of failure are summarized in Table 2-2. (Roche et al., 2005)

Table 2-2 Consequence of Failure Criteria (Roche et al., 2005)

Consequence Assessment	Sewer Assets	Water Supply Assets
Social Impact	• Immediate threat to public health and safety • Visibility of sewage spill • Type of customers affected • Number of customers affected by loss of service • Duration of loss of service	• Immediate threat to public health & safety • Location of watermain break • Type of customers affected • Number of customers affected by loss of service • Duration of loss of service
Environmental Impact	• Quantity of sewage spilt to the environment • Impact to the receiving environment • Release of toxic liquid chemicals or noxious • gases	• Quantity of water lost to the environment • Impact to the receiving environment • Release of toxic liquid chemicals or noxious gases
Economic Impact	• Difficulty of asset repair • Cost of asset repair • Insurance claims from property damage or business loss • Likelihood of fines by EPA	• Difficulty of asset repair • Cost of asset repair • Insurance claims from property damage or business loss • Likelihood of fines by EPA

Halfawy (2008) used the term “risk factor” to describe the consequence of failure. Risk factor was determined on a range of one to five, based on factors such as sewer type, function, diameter, depth, soil type, seismicity, land use, road classification, traffic volume, proximity to critical assets, and overall socioeconomic impact. Risk factor was multiplied by the failure index to reach a risk index.

2.4.3 Risk Assessment for Road Assets

Transportation agencies, private consultants, among others, typically utilize special tools to support or perform risk assessment analysis. In order to quantify the risk associated with various factors of an infrastructure project, different evaluation methods might be applied.

Assessment of previous accident locations is the traditional approach to identifying risk on roads. Recently researchers have adopted a new approach to assess risk on the basis of road and roadside features. Reasons for this newer approach include a move to the safe system approach, duty of care considerations, the declining number of crashes that occur in black spots, database issues and the availability of accurate information relating to risk factors and the contribution they make to safety (Roper and Turner, 2008).

Most of the risk assessment for roads originating in Canada, Australia, Europe and the United States focus on safety issues and utilize simple safety performance indicators (e.g., collision density and collision rate) to define the road safety risk levels.

2.5 Condition Assessment and Performance Evaluation

2.5.1 Water Assets

Pipes in a water distribution network are characterized by increasing the frequency of breakage and failure over time mainly due to deterioration, which would reduce the hydraulic network capacity and the quality of service. It would also increase operation and maintenance costs and water losses in the water distribution system. Al-Aghbar (2005) stated that the causes of watermains deterioration is due to four main reasons; aging of water distribution infrastructure due to the surrounding environmental factors, inadequate preventive maintenance and asset management programs, inadequate funds and changed municipality priorities, and finally lack of information and staff. As a result, several models have been developed and improved to predict deterioration in watermains. Deterioration rate in watermains is affected by different physical, environmental and operational factors (Al Barqawi and Zayed, 2008).

Condition assessment of watermains is challenging compared to other infrastructure assets because they are typically underground, operated under pressure, and mostly inaccessible. The purpose of a condition rating system is to objectively rate or scale the current condition of the buried pipes. Al Barqawi (2006) conducted a comprehensive literature review on various efforts related to watermain condition rating. Al Barqawi (2006) condition assessment model, using artificial neural network (ANN) and analytical hierarchy process (AHP), is employed within this study in order to set up rehabilitation priority for watermains. Various factors are incorporated in the developed model, such as physical (pipe type, size, age, breakage rate), environmental (Cathodic protection, ground water level, soil type, surface type, and road type), and operational (Hazen-Williams factor, operational pressure).

2.5.2 Wastewater Assets

Condition assessment of storm and wastewater collection system generally focus on three perspectives: 1) structural integrity (physical condition); (2) functional integrity (service condition); and (3) hydraulic adequacy (capacity). A number of sewer condition rating systems are available. The Water Research Centre (WRc), the Water Environment Federation/American Society of Civil Engineers (WEF/ASCE) and the National Research Council Canada have all published manuals and guidelines for the assessment and evaluation of sewer systems. These systems can be used “off the shelf” or can be customized and adapted to the specific needs of individual municipalities or utilities (InfraGuide, 2004). These manuals and guidelines include:

- Manual of Sewer Condition Classification (WRc, 2001);
- Guidelines for Condition Assessment and Rehabilitation of Large Sewers (NRC, 2001);
- Manuel de standardisation des observations-inspections télévisées de conduites d’égout (CERIU, 1997);
- Existing Sewer Evaluation & Rehabilitation (ASCE, 1994); and
- Manhole Inspection and Rehabilitation (ASCE, 1997).

The WRc standard is the most commonly used within municipalities (Chughtai and Zayed, 2011); therefore, WRC (2001) condition assessment manual is employed within this research in order to set up rehabilitation priority for wastewater assets.

2.5.3 Road Assets

Road Performance prediction models are used in pavement management systems to predict the performance of the asset and to model post rehabilitation performance. Road condition assessment criteria include: pavement quality index (PQI), riding comfort index (RCI), international roughness index, structural adequacy index (SAI), surface distress index (SDI) and pavement serviceability index (Falls et al. 2006).

Pavement Quality Index (PQI) provides an overall indication of the condition of a pavement with regard to present and future service to the user. The present service to the user is reflected in the Riding Comfort Index (RCI) values whereas the future service is reflected in the Surface Distress Index (SDI) values. The PQI represents a combination of the sectional RCI and SDI values (Stantec, 2005).

PQI is primarily represented by its SDI value for most pavement sections (e.g. minor collector, local commercial, and local residential). PQI is adjusted downward for pavement sections that show poor ride characteristic, the magnitude of the adjustment depends on RCI of each section. On the other hand, PQI of the other section of the road network is primarily represented by its

RCI value, as these are sections that are traveled at higher speeds. A downward adjustment is also made for pavement sections that show distress. The magnitude of the adjustment depends on the amount of distress (SDI value) (Lashlee et al. 2004).

Pavement Performance models have been categorized into four basic types: mechanistic, mechanistic–empirical, regression analysis, and subjective models (Haas et al. 1994). The United States Governmental Accounting Standards Board (GASB 34) has introduced a fifth performance model based on financial models that can be straight-line, declining balance, or other forms of accounting-based depreciation.

2.5.4 Level of service

As defined "*Levels of service statements describe the outputs or objectives the organization intends to deliver to customers and includes measures at the corporate, customer and asset levels of the organization*" (IIMM, 2006).

Level of service measures the condition and /or performance of individual assets as well as the overall condition and /or performance of the road/ water /sewer network. LOS measures are generally specified in customer / client service terms related to safety, preservation, convenience, aesthetics, comfort, and/or mobility.

It can be difficult to determine the correct level of expenditure on capital maintenance – the capital expenditure required to maintain the current level of service to the community. Too much investment is likely to result in assets being replaced unnecessarily, leading to higher prices and little benefit for customers. Too little investment is likely to mean a gradual decline in the assets performance with a similar impact on customer service. An example of the relationship between Level of service provided and level of investment required, adopted from Washington State Department of Transportation (WSDOT), are shown in Figure 2-4. WSDOT uses an approach that defines LOS and priority in accordance with their contribution to the program goals for safety, reliability, protecting the investment (WSDOT, 2004).

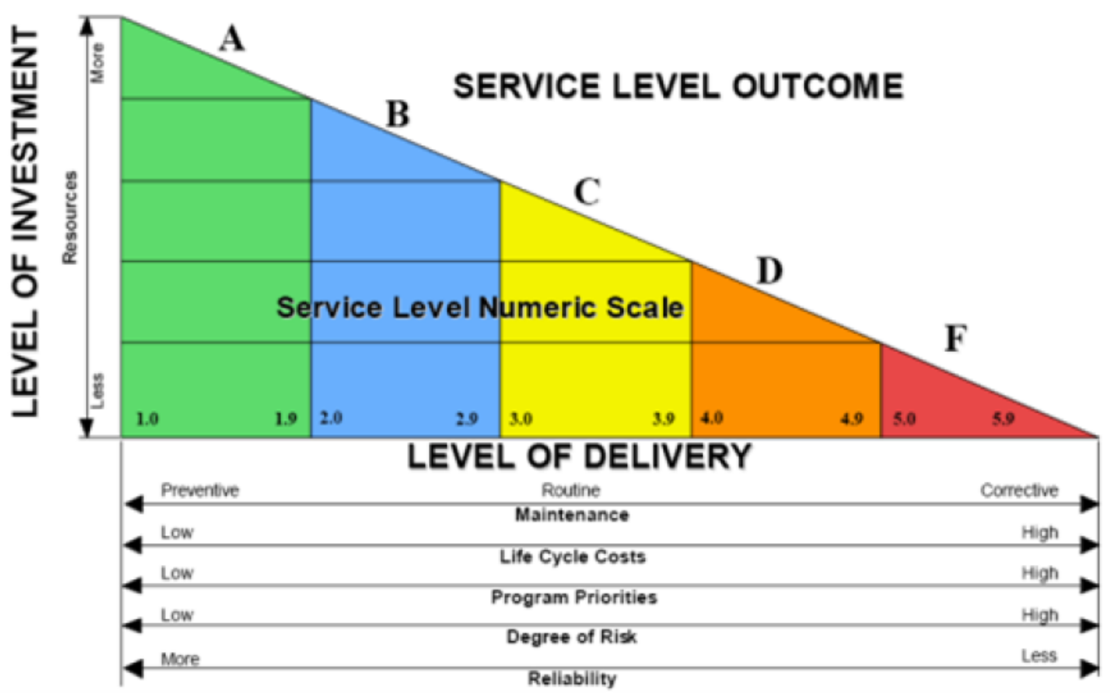


Figure 2-4 Service Level Effectiveness (WSDOT, 2004)

The IIMM Manual, (2006), defined three tiers for Level of service, 1) Corporate / Strategic, 2) Customer or Client Driven, and 3) Asset or Technical LOS. These tiers need to be established in a manner that clearly illustrates how corporate objectives are linked to asset objectives and that the assets provide the levels of service needed to meet customer needs. Figure 2-5 shows an example of how a general concept of Corporate/Strategic objectives are linked to customer values and asset performance measures criteria (Thompson, 2012)

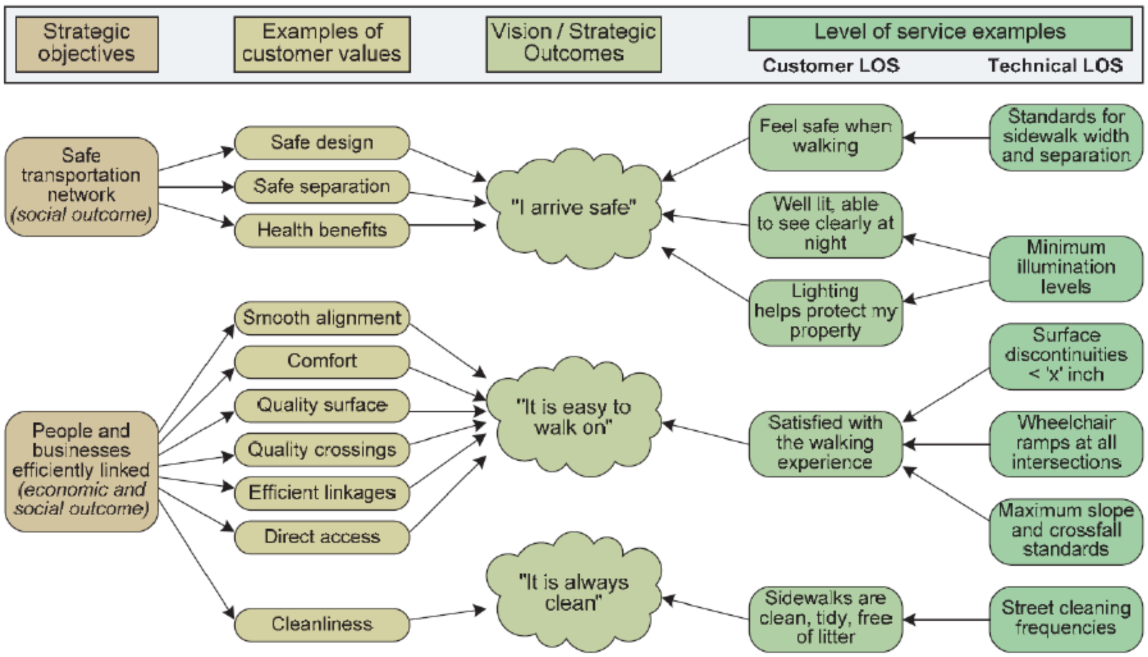


Figure 2-5 Derivation of Levels of Service From Strategic Objectives (Thompson, 2012)

Municipalities are undergoing tremendous change in the way they conduct their business as they become more customer-oriented and business- focused. These changes are evident in the various departments within municipalities. Zimmerman and Stivers (2007), mention that recently transportation agencies have shifted their focus from expansion and new construction to maintenance and system preservation. As part of this transition, many transportation agencies are updating their Maintenance Management Systems (MMS) to better link customer expectations to performance-based program objectives. Similarly in

2010 the City of London, Ontario adopted a service-based budget approach for all its assets to be able to link expenditure to service delivery, thereby improving service to its customers.

2.6 Framework for Prioritization

Prioritization has many different identities and based on the source has different properties, outcomes, and processes. These can vary from simply asking questions of management to more specific and ordered processes. While various methodologies have been proposed many deal with different aspects of strategic planning but share many of the same shortcomings. Preference for which factor is more important for a particular scenario can differ among a group of experts. In order to account for these differing opinions and create a robust solution, prioritization should be performed in a group situation. This aggregation of the opinions of a large sample of professionals and decision makers ensures that the final solution is independent of the individual concerns of any one member. Raczynski (2008) summarized the process of how the voters perform this task and how the information is collected.

Rank Ordering: The first method for establishing priorities of the attributes is to have the voters in the group place all the goals in order from most to least important. A score can then be given to each goal based on the ranking given to it (Fishburn and Gehrlein, 1976). The major disadvantage to this method is that with the voters simply laying out the order of priority and not the degree then the final weights may not be true representations of the importance that the voters feel.

Cumulative Voting (CV) is a method that allows the users to distribute points among the alternatives. The points can be allocated in any amount, and the voters are allowed to spread them however they see fit. The vote totals amongst the population are then summed to give the overall group decision of the important rankings. One disadvantage to this methodology is that it can be difficult for a voter to determine exactly how to distribute the points (Raczynski, 2008).

The Delphi Technique was developed by the RAND Corporation to perform technological forecasting (Tersine and Riggs, 1976). The idea was that a group of experts could be more accurate than any of them individually. In order to remove bias from the group, the participants are not given any knowledge of who else is participating and, thus, there are no in-person group discussions. Instead, information is passed through a third party in the form of questionnaires which also has the added benefit of not requiring the participants to be in geographical proximity of each other. Experts answer questionnaires in two or more rounds. After each round, the third party provides an anonymous summary of the experts' forecasts from the previous round as well as the reasons they provided for their judgments. Thus, experts are encouraged to revise their earlier answers in light of the replies of other members of their panel. It is believed that during this process the range of the answers will decrease and the group will converge towards the "correct" answer. Finally, the process is stopped after a pre-defined stop criterion (e.g. number of rounds, achievement of consensus, and constancy of results) then the mean scores of the final rounds determine the results.

Analytic Hierarchical Process (AHP) was developed by Thomas Saaty in 1971 as a methodology for prioritizing alternatives based on the relative rank amongst them. It has achieved widespread use in the management community and is most commonly used in the software solution Expert Choice. The ability to connect various levels of a hierarchy and relate lower level items to higher level ones is one of AHP's most dominant features. The first step in AHP is to create the hierarchy, which will define the levels of the analysis to be performed. Once this has been accomplished pair wise comparison matrices are made among all the alternatives. With the matrix completed for each of the criteria the calculations can be performed to elicit the rankings of the alternatives. The eigenvector of each of the criteria matrix is computed which represents the relative importance of each alternative. The impact of the alternatives across all the criteria is determined by weighting the eigenvectors according their importance to the decision maker and summing them. A single value for each alternative is the result and the larger the value the higher the ranking relative to the rest of the field (Wind and Saaty, 1980).

Multi Attribute Utility Theory (MAUT) approach is an attempt to apply objective measurement to decision-making. The basic hypothesis of MAUT is that in any decision problem, there exists a real valued function or utility (*U),* defined by the set of feasible alternatives that the decision-maker seeks to maximize (Olson, 1996). Each alternative results in an outcome, which may have a value on a number of different dimensions. MAUT seeks to measure these values, one dimension at a time, followed by an aggregation of these values across the dimensions through a weighting procedure. The simplest and most widely used aggregation rule is to take the weighted linear average. In this case, each weight is used in conjunction with each criterion value to produce the final utilities (Zietsman et al., 2006).

2.7 Optimization Algorithms

When the serviceability or quality of a municipal infrastructure component such as road (pavement), watermains, or wastewater pipes reaches an unacceptable or intervention level, some actions are needed. If sufficient funds are available, all actions can be taken. However, for most municipalities, the usual situation is constrained budget. In such cases, priorities have to be set to answer the following questions:

- Which projects should be conducted?
- What repair/replacement method should be applied?
- When should the work be done?

Optimization algorithms are used to search the optimal strategy for any given network subject to predefined constraints. Nunoo (2001) identified four major algorithms used in infrastructure management specially pavement: linear, non-linear, integer and dynamic programming. In the recent decade, evolutionary programming techniques, such as Genetic Algorithms, and Neural Networks techniques, were adopted by researchers and practitioners. The selection of the appropriate algorithm depends on the type and number of decision variables, the form of the objective functions and constraints, and whether a decision must be made in sequence. The main features of these techniques and their disadvantages are presented in Table 2-3 (adapted from Nunoo (2001)).

Table 2-3 Optimization Techniques Characteristics

Optimization Method	Features / Advantages	Disadvantages
Linear Programming	• Objective function and constraints are formulated as linear equations • Decision variables are continuous. • Most common method used in pavement management systems. • Simple	• Cannot handle a large number of decision variables. • Cannot handle combinatorial problems
Non-linear Programming	• Objective function and constraints are formulated as non-linear equations	• Cannot handle a large number of decision variables. • Cannot handle combinatorial problems
Integer programming	• Objective function and constraints are formulated as linear and / or non-linear equations. • Decision variables are constrained to take integer value (0 or 1). Results in a decision matrix that is composed of a series of 0's and 1's	• Cannot handle a large number of decision variables. • Cannot handle combinatorial problems
Dynamic programming	• DP is a mathematical technique for making a sequence of interrelated decisions. • No existing standard mathematical formulation. • It provides a systematic procedure for determining the optimal combination of decisions. • It provides a great computational savings over using exhaustive enumeration to find the best combination of decisions, especially for large problems	• It requires formulating an appropriate recursive relationship for each individual problem. • Difficulty in maintaining identity of individual assets segments

Optimization Method	Features / Advantages	Disadvantages
Genetic Algorithm	• Based on natural selection and natural genetics. • GA usually starts from a population of randomly generated individuals. In each generation multiple individuals are selected from the current population (based on their fitness), and modified (recombined and possibly randomly mutated) to form a new population to evolve towards a better solution. • Capable of solving combinatorial problems. • Can handle a large number of decision variables, flexible in defining the objective function.	• Does not generate a true optimal solution
Heuristic Method	• Used in place of true integer programming because of the limitation on the size of the problems that can be handled with true integer programming. • Approximation to true optimization techniques	• Does not generate a true optimal solution

2.8 Summary

Asset managers are faced with many challenges regarding when and how to inspect, maintain, repair and replace a diverse set of existing infrastructure assets cost effectively. There are a few tools available in the form of standards, guidelines, technical literature, or best practices to assist them in their decision-making. However, it is extremely difficult for organizations to evaluate all these solutions for suitability that meets their needs, as it is not specific to their needs / issues. It is recommended that a specific decision support framework for implementing these solutions be developed.

There are several applications in development regarding municipal infrastructure management systems (Lee and Deighton (1995); Quintero et al.

(2003); Ferreira and Duarte (2005); and Halfawy (2008)). Ferreria only examined the road network using his proposed technique; failing to introduce optimization in his proposed model. On the other hand, Halfway emphasizes data modeling and integration of software tools, rather than the details of individual integration processes (e.g. risk assessment, renewal planning, and optimization). Halfway did not identify decision trees and/or business barriers between various municipal departments. Additionally there are no accepted standards or practices for dealing with spatial issues.

Based on the literature review and background presented the following should be noted: (a) Few researches have been reported for assessment models that integrate road water, and sewer network decision making in a one comprehensive approach, (b) Lack of an integrated model that considers risk, performance and optimization for road, water and sewer network, (c) Lack of an integrated tool that considers integrated decision making aspects throughout the entire life cycle of infrastructure .

Several reports/manuals have described the processes needed to implement municipal infrastructure management programs e.g. Lemer (1998), InfraGuide (2003a), and IIMM (2006). Although these high-level definitions provided insight into the main processes, they did not provide sufficient details about their organization, interrelationships, and integration information requirements. Therefore, formalizing a more detailed process and model is required.

CHAPTER 3: RESEARCH METHODOLOGY

The plan to achieve the objectives of this dissertation consists of three main phases, as shown in Figure 3-1: (1) conduct literature review of current asset management practices; (2) develop integrated asset management framework and model; and (3) develop prototype and implementation. Each phase will be further discussed in the sections below.

Figure 3-1 Research Framework

3.1 Literature Review for Current Asset Management Practices

Literature Review, as discussed in chapter 2, included: reviewing the existing state-of-the-art, to achieve a thorough understanding of the area of interest (asset management practices), and analyzing the approaches taken in decision-making for corridor rehabilitation of road, water and wastewater network. Additionally, perform a review of commercial software packages on asset / maintenance management by studying their operating characteristics and functionalities. Finally, hold discussions with asset management professionals to seek knowledge from their experience and feedback.

3.2 Integrated Asset Management Framework and Model

The Integrated Asset Management Framework is illustrated in Figure 3-2. This framework employs the following four main tasks:

(Task-1) Data collection and analysis: Data collection included preparing questionnaires, conducting interviews, choosing a case study and getting access to GIS geodatabase, maintenance records, and various technical reports. Data analysis involved identifying various integrated segmentation options and conducting GIS spatial data analysis.

(Task-2) Perform integrated risk assessment: This task required developing a hierarchy of the major criteria/factors that contribute to risk for each Road / Water / Sewer (R/W/S) asset. The weight of each factor is determined using the Analytical Hierarchy Process (AHP). The expected outcome of this task is an integrated overall Risk Index for road, sewer, and water assets. These indices are amalgamated and grouped into an overall integrated Segment Risk Index using K-means Clustering technique.

(Task-3) Conduct integrated performance evaluation: Identify key performance indicators for each asset class; establish and measure performance, and finally link the key performance indicators to a desired level of service using fuzzy logic. The expected outcome of this task is an integrated Client Driven Performance Measures Index.

(Task-4) develop decision support model (prioritization using optimization): This task utilizes the available replacement / rehabilitation actions, sets priorities for integrated corridor rehabilitation, implements optimization of repair/renewal cost and defines the best replacement interval via integer programming (IP).

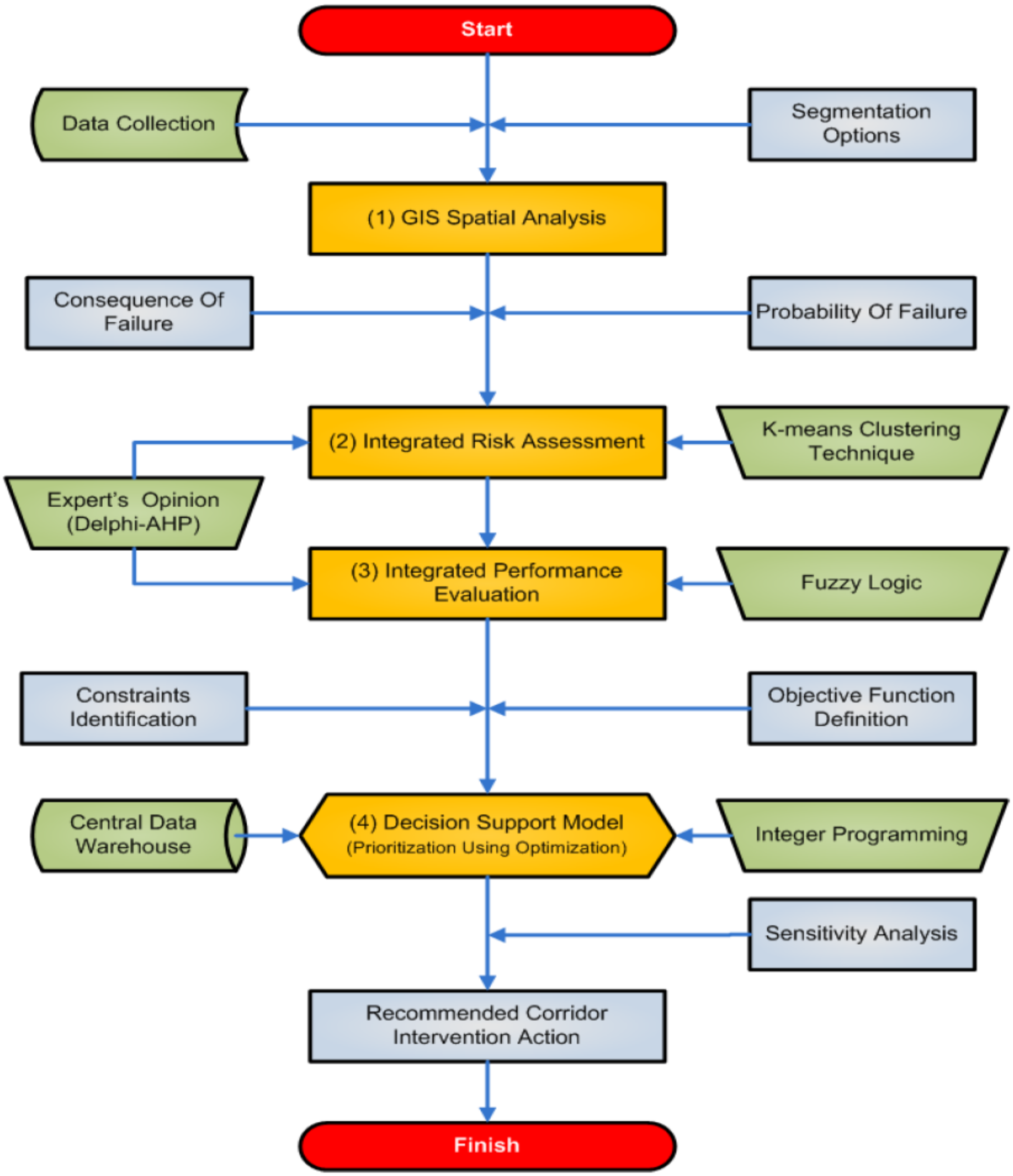


Figure 3-2 Integrated Asset Management Methodology

3.2.1 Data Collection and Analysis

In order to demonstrate the model features, a case study was developed using information on the City of Guelph, Ontario, Canada. The City of Guelph has a population of approximately 115,000. The total operating budget is approximately $255 million with a capital budget of roughly $81 million. The city of Guelph was selected as it provide a good representation for small to medium size municipalities based on population, demographics and geographical location. The data collected from the city databases needed some manipulation and preparation before using it in the proposed decision support system.

(i) Conduct GIS Spatial Data Analysis

The proposed decision support framework required the preparation of centralized asset data repositories to integrate spatial and non-spatial data. Spatial data analysis is required to prepare attributes in a convenient structure. Figure 3-3 shows a sample spatial data analysis procedure which is used for further analysis of each module. The overlaying approach involves joining multiple municipal departments' assets to develop coordinated and optimized plans for the management and renewal of spatially located infrastructure assets (e.g. watermains, sewermains, and road assets in the right of way). The intersection of a buffered road layer with the centriod of water and sewermain layer facilitates the mapping of water and sewer asset attributes to the road segments. Similarly, the intersection of a buffered layer of watermains segment with sewer and road segment has been linked.

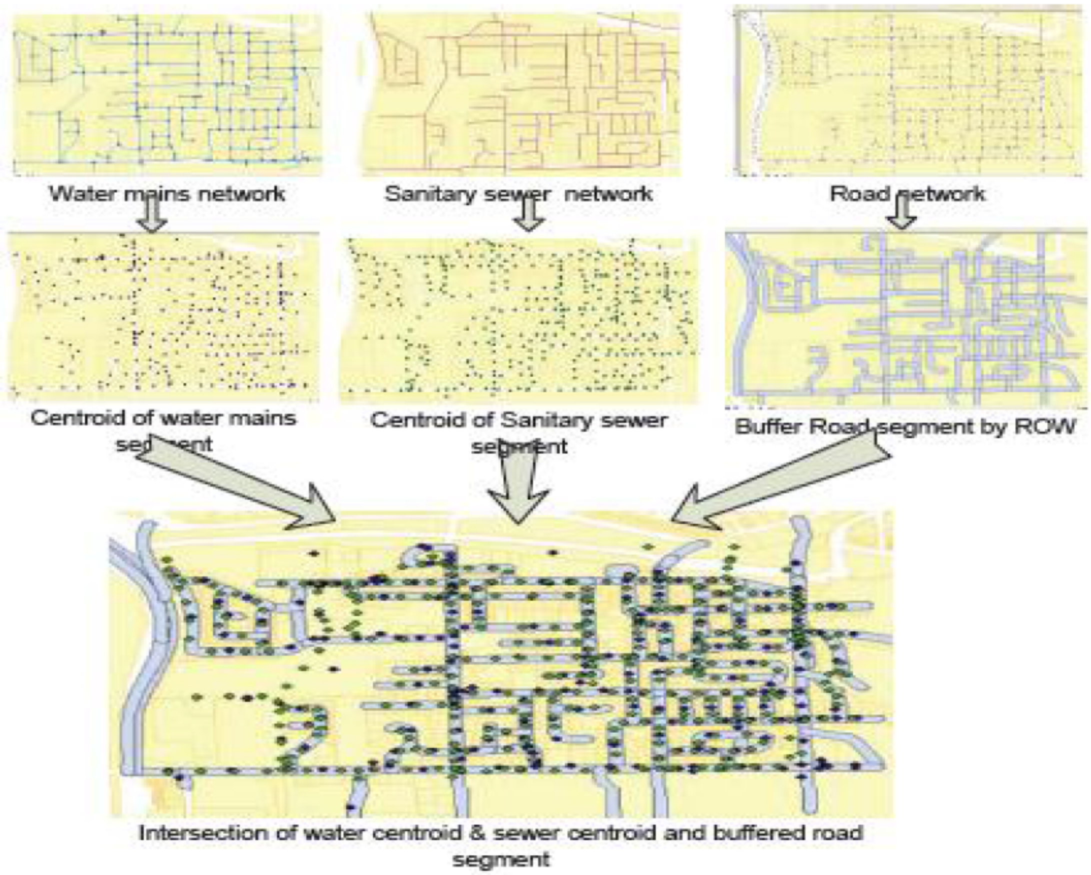


Figure 3-3 Sample Spatial Data Analysis Procedure

(ii) Define Segmentation Options

The definition of an infrastructure 'unit' of inventory plays a pivotal role in information management practices. For example, a watermain 'unit' is the smallest unit of asset inventory that forms the base of the data management system used to store and organize watermain data. It is a typical practice with linear network infrastructure to divide the network into smaller more manageable units. These will be referred to as segments. Road, water, and sewermain segments are developed from as-built drawings that are in turn digitized into GIS format. The existing segmentation in many municipalities is based on splitting a physical asset as follows: sewermains are split from manhole to manhole, while watermains are split at any recorded feature (e.g. bends, tees, reducers, valves, etc...), and roads are split at each intersection. The result of this segmentation practice is a large variability in the length of each of the inter-related segments.

The selection of the most suitable rehabilitation decision depends on the segmentation approach used for road, water and sewer assets. Figure 3-4 shows a systematic approach for defining the available corridor rehabilitation segmentation option. For example, if a sewermain is the driving asset for implementing corridor rehabilitation then the following options will be considered for replacement: I) replace sewer segment from manhole to manhole and the equivalent portion of water and road segment length only (in some cases, this option might not be practical, each case will have to be dealt with separately); II) where a sewer segment is shorter than a water segment; replace sewermains equivalent to the water segment length, and road segment equivalent to water segment (utilizing this option might result in replacement of non-critical asset, each case will have to be dealt with separately) ; III) replace sewer segment from manhole to manhole, water segment from node to node, and road segment equivalent to the longer sewer / water segment, each of these segmentation options will be considered for further analysis and optimization of the most cost effective option.

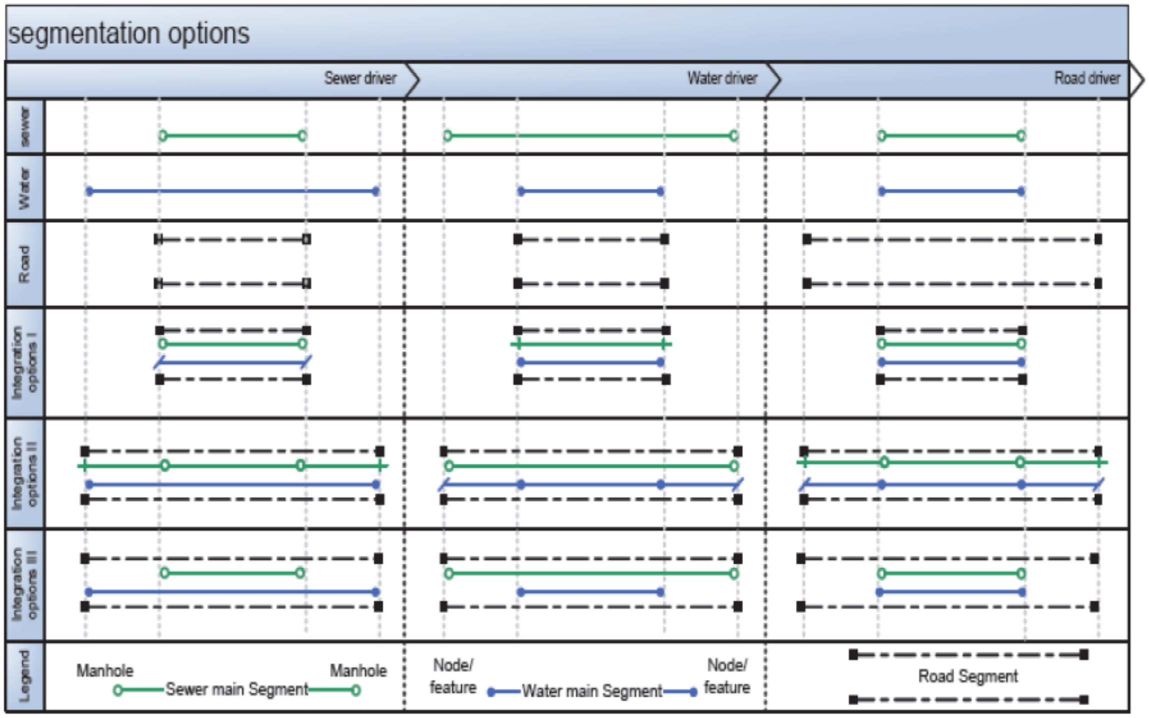


Figure 3-4 Integrated Segmentation Options

3.2.2 Integrated Risk Assessment Framework

Risk assessment, based on the objective assessment of the probability and consequences of asset failure, represents a practical and effective means of identifying and prioritizing capital and maintenance requirements. Although failure modes will differ, the risk dimensions should remain constant (Economic, Operational, Social, and Environmental). This framework will allow for inter-asset alignment and comparison of results and will support consistency in risk-based planning and prioritization of infrastructure inspection, maintenance, and capital needs. The assessment was broken into three main steps as shown in Figure 3-5.

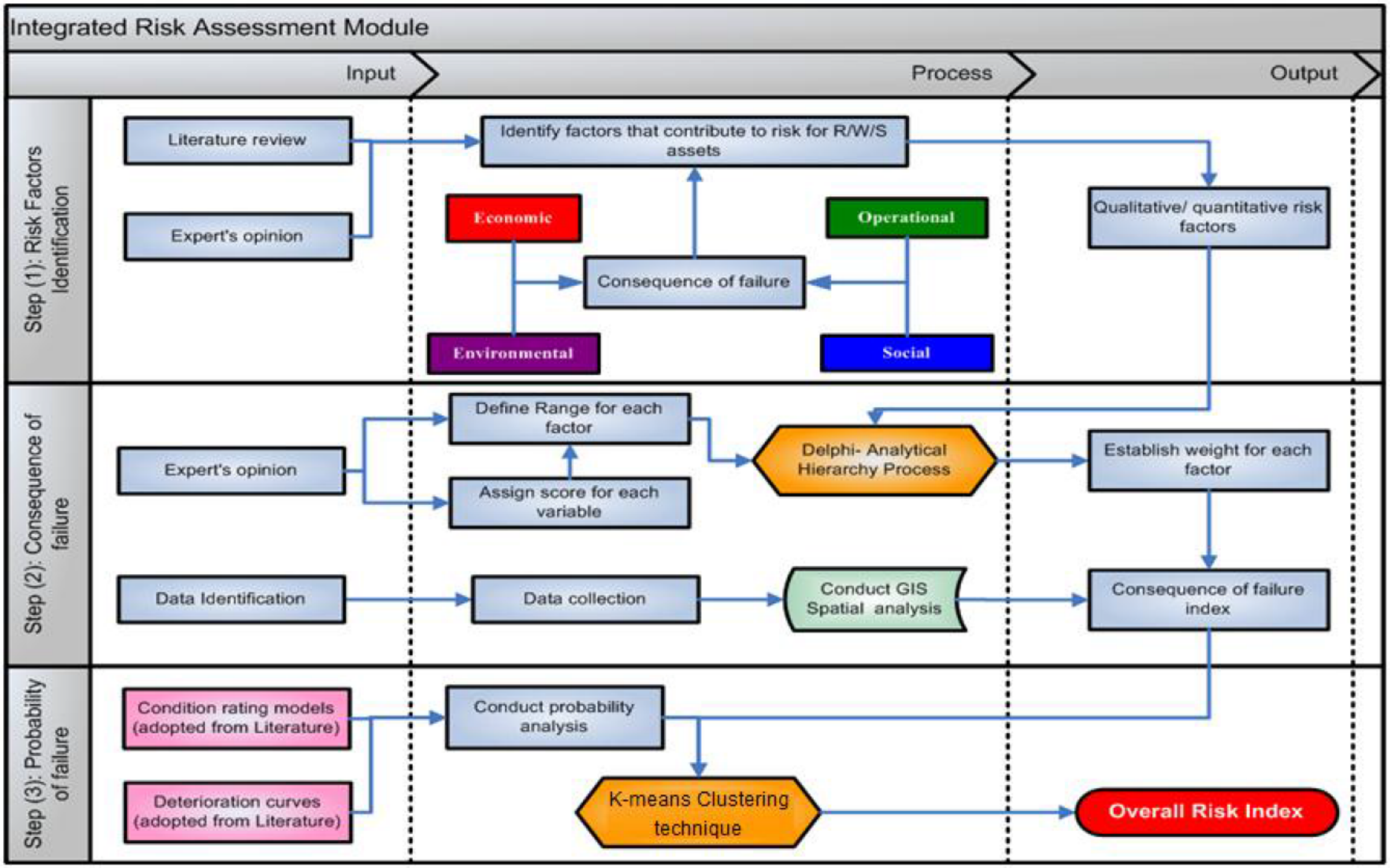


Figure 3-5 Integrated Risk Assessment Framework

Step (1): Identification of Risk Factors

Risk Factors are a combination of qualitative and quantitative factors. Two approaches are used to conduct this step: (a) Literature review; and (b) Expert's opinion. A stakeholder interview / workshop was used to identify current practice, issues and challenges, and confirm risk assessment objectives. A comparative analysis was performed to identify gaps between current and desired states.

Step (2): Consequence of Failure

The parameters affecting cost of rehabilitation and replacement of R/S/W infrastructure assets were selected based upon four overall Consequence of Failure (COF) indices as shown in Figure 3-5 Integrated Risk Assessment Framework, as follows:

- ***Economic:*** influence of the asset's failure on monetary resources
- ***Operational:*** influence of the asset's failure on operational ability
- ***Social:*** influence of the asset's failure on society
- ***Environmental:*** influence of the asset's failure on the environment

Next, the parameters that influence each of the previous consequence of failure indices were established.

Consequence of failure assessment methodology aims at transferring these qualitative and quantitative factors into a point system. A framework was then developed for the risk assessment by establishing a standard risk scoring system for various risk factors (Economic, Operational, Social, and Environmental), and determining the appropriate weighting for each risk factor based on its impact or consequence of failure (CoF). The establishment of risk indices, parameter scoring and weightings were based on expert opinion using a mixed Delphi-Analytical Hierarchy Process (Delphi-AHP) approach adapted from Tavana et al., (1993).

Step (3): Probability of Failure

The probability of failure and failure modes differ for each infrastructure asset (road, sewer, and water segment). Independent infrastructure asset based condition rating and deterioration models are required in order to forecast future condition and current likelihood of failure. This step builds on the existing condition rating and deterioration models available in literature; and adopts a suitable model for road, sewer and water infrastructure assets. The risk model can be formulated as Equation 3.1.

$$\text{Risk} = \text{Probability of Failure} \times \text{Consequence of Failure} \qquad \text{Equation3-1}$$

The final outcome of this model is an overall Risk Index for road, sewer, and water assets. Individual results are amalgamated and grouped into an overall integrated Segment Risk Index using *K-means Clustering technique* (K-means). K-means is an unsupervised learning algorithm that solves the clustering problems and is a powerful technique to solve many real world problems (MacQueen, 1967). They have the ability to learn from experience in order to improve their performance and to adapt themselves to changes in the environment. Unsupervised networks learn on their own. Data sets are presented to such networks and they learn to recognize patterns. The results are grouped into an overall integrated Segment Risk Index.

3.2.3 Integrated Performance Evaluation Framework

Infrastructure exists to serve its users; performance measures are used to link asset and system operation to business objectives. Performance evaluation aims to define a baseline for service levels achieved by various asset classes investigated in this research. Performance evaluation is divided into two stages as shown in Figure 3-6, Step (1) Develop a Customer/Client Driven Performance Measures Index; Step (2): Conduct economic loss calculation. The economic loss calculation is used in the subsequent Decision Support Model.

Step (1): Develop a Client Driven Performance Measures Index

Incorporation of Client Driven Performance Measures (CDPM) with Decision Support framework will aid municipalities in producing improved renewal plans that comply with service standards, applicable codes, and regulations. In this research, a framework of the development of CDPM in municipal infrastructure systems is introduced. A combination of Analytical Hierarchy Process (AHP) and fuzzy logic technique are utilized to model the CDPM. The developed framework is then applied to calculate the CDPM Index for the roads, sewer and water infrastructure assets.

Client Driven Performance Measures can be summarized by identifying key performance measures for each asset class, establishing and measuring performance and finally linking key performance indicators to a desired level of service.

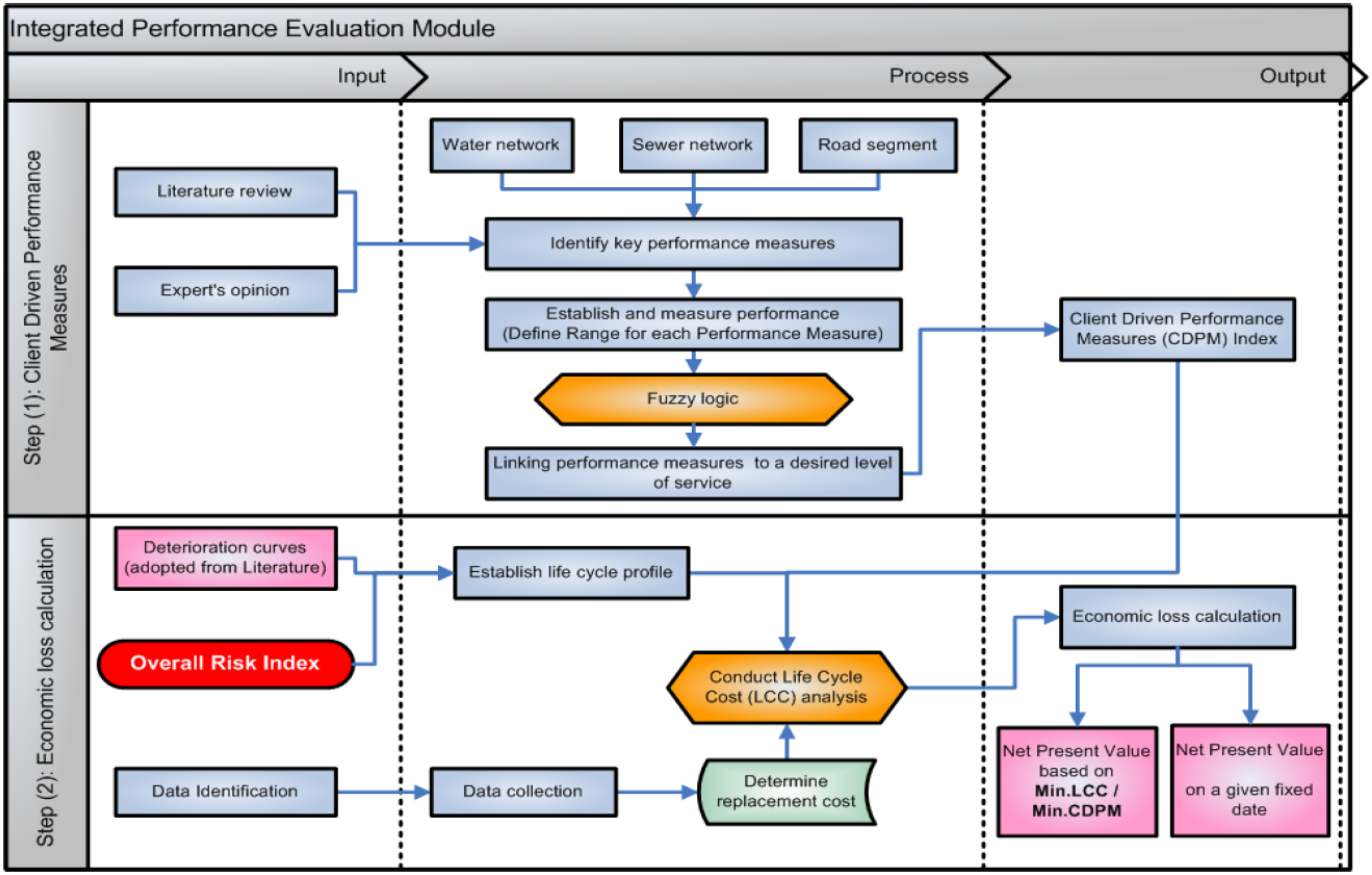


Figure 3-6 Integrated Performance Evaluation Framework

Asset management experts were engaged to examine business drivers and identify how 'service' is defined for each asset class, rationalize performance measures that link business goals with infrastructure operation, and establish 'scales' and threshold values representing the acceptable operating range for each asset.

Step (2): Economic Loss Calculation

The main purpose of the Economic Loss analysis is to estimate the economic loss / gain of fixing the date of the rehabilitation / replacement of road, sewer and /or water segment in comparison to rehabilitating / replacing the R/W/S segment in the year following when the Minimum Life Cycle Cost (Min-LCC) criterion or the Minimum Client Driven Performance Measures (Min-CDPM) criterion is met. The Model is used as a tool to estimate the economics of advancing or deferring the date of rehabilitation/replacement of any R/W/S segment.

Economic Loss modeling aims at estimating the probabilities of future failures as a function of time. Given the current overall Risk Index, condition assessment of any selected R/W/S segment, and the date of the last failure, the proposed model aims at estimating the probability of the occurrence of subsequent failures as a function of time in years using deterioration curves. There are two numerical outputs: the expected Net Present Value of rehabilitation/ replacement based on Min-LCC / Min-CDPM criterion, and the expected Net Present Value of rehabilitation or replacement on a given fixed date.

3.2.4 Development of Decision Support Model

A final optimized decision-making framework for each lifecycle option of the integrated corridor rehabilitation is achieved through the integration of risk management scoring, condition assessment, performance management, and economic loss of remaining service life. While there are several optimization options available, optimized decision making is computationally intensive requiring hundreds of calculations. The selected integer programming approach is influenced by the availability of software capable of supporting this type of analysis and data required to drive it.

(i) Optimization Framework

All optimization problems have several elements in common. They all have (1) decision variables, the variables that decision makers can choose, either directly or indirectly, which affect the value of the objective function. (2) Objective function, whose value is to be optimized (minimize or maximize). (3) Constraints, a set of constraints that allow the unknowns to take on certain values but exclude others. In searching for the values of the decision variables that optimize the objective function, we must choose values that satisfy the constraints.

Integrated infrastructure management has *multiple objective functions.* Optimizing integrated infrastructure rehabilitation requires the simultaneous optimization of more than one objective function such as minimizing replacement cost, minimizing the economic loss of early replacement of an asset, maximizing network condition rating, minimizing consequence of failure and maximizing performance. In practice, problems with multiple objectives are reformulated as single-objective problems by either forming a weighted combination of the different objectives or replacing some of the objectives with constraints. Optimization using integer programming (IP) allows searching for decision variables that maximize the objective function while satisfying certain constraints (set by decision trees). Figure 3-7 illustrates the proposed integrated decision-making / optimization framework.

(ii) Decision Support Model Output

The purpose of this module is to equip the asset manager with a consistent methodology for decision-making during the integrated corridor rehabilitation planning cycle. Within a planning cycle, the asset manger must make one of three decisions for each asset in the road right of way:

1. Schedule Intervention: This action is triggered when there is enough information to reasonably conclude that risk is unmanageable and that repair, rehabilitation or replacement is required. This action is divided into two sub actions a) corridor rehabilitation intervention*:* this raises a flag for risk of failure for two or more assets and requires a scheduled intervention, or b) single asset intervention*:* this flags an immediate action for one asset only to prevent its failure.
2. Schedule Inspection: This action is triggered when a) the current assessment information is uncertain and suggestive of a deteriorated condition state, and b) the risk associated with operating the road / pipe segment cannot be tolerated at this level of information uncertainty.

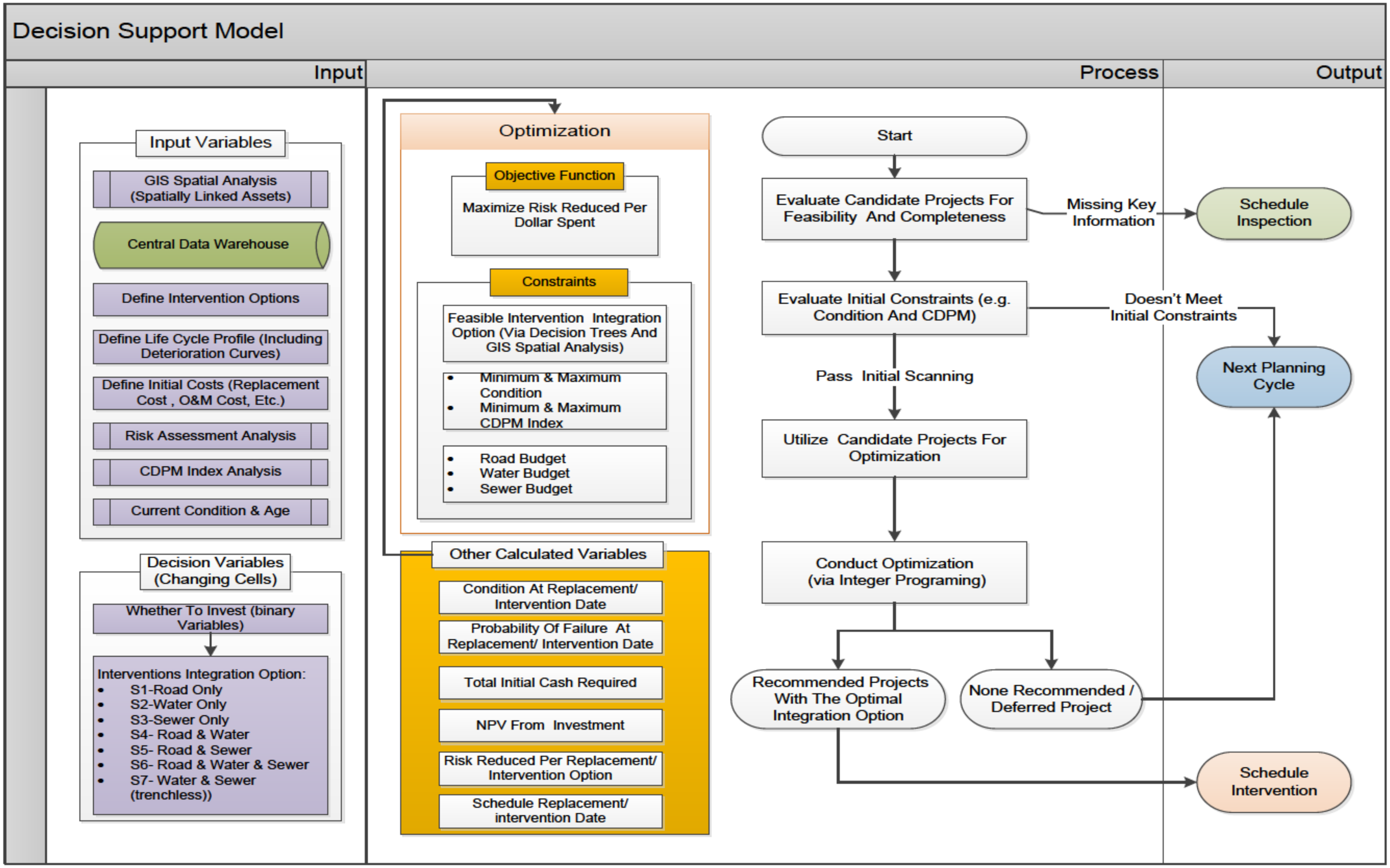


Figure 3-7 Decision Support Model & Optimization Framework

3. Revisit at Next Planning Cycle: This action is triggered when current assessment information (and its certainty) has not exceeded the risk threshold of road / pipeline operation. This is equivalent to a ‘do-nothing’ scenario. This action is divided into two sub-actions based on a combination of risk level and condition information uncertainty:

    a) Next planning cycle within 3-5 years, this action is triggered for road / pipe segments having high and/or medium priority category.

    b) Next planning cycle within 7-10 years, this action is triggered for road / pipe segments having low priority category.

3.3 Prototype Development and Implementation

Prototype development and implementation involves definition of architecture and user interfaces for the integrated system. The prototype is based in MS-Access and MS-Excel applications that are linked to ESRI ArcGIS software to visualize results. The integrated prototype application is implemented as a set of modules. Each module addresses one stage of the integrated planning process as shown in Figure 3-8. The prototype utilizes data from various data sources (e.g. computerized maintenance management system (CMMS), condition assessment, physical data, financial data, etc.) then stores all relevant attributes in one central Microsoft Access database. It provides a common information interface for road, water, and sewer assets (one window approach) using the GIS platform. The prototype can then reuse the stored data during the reporting process.

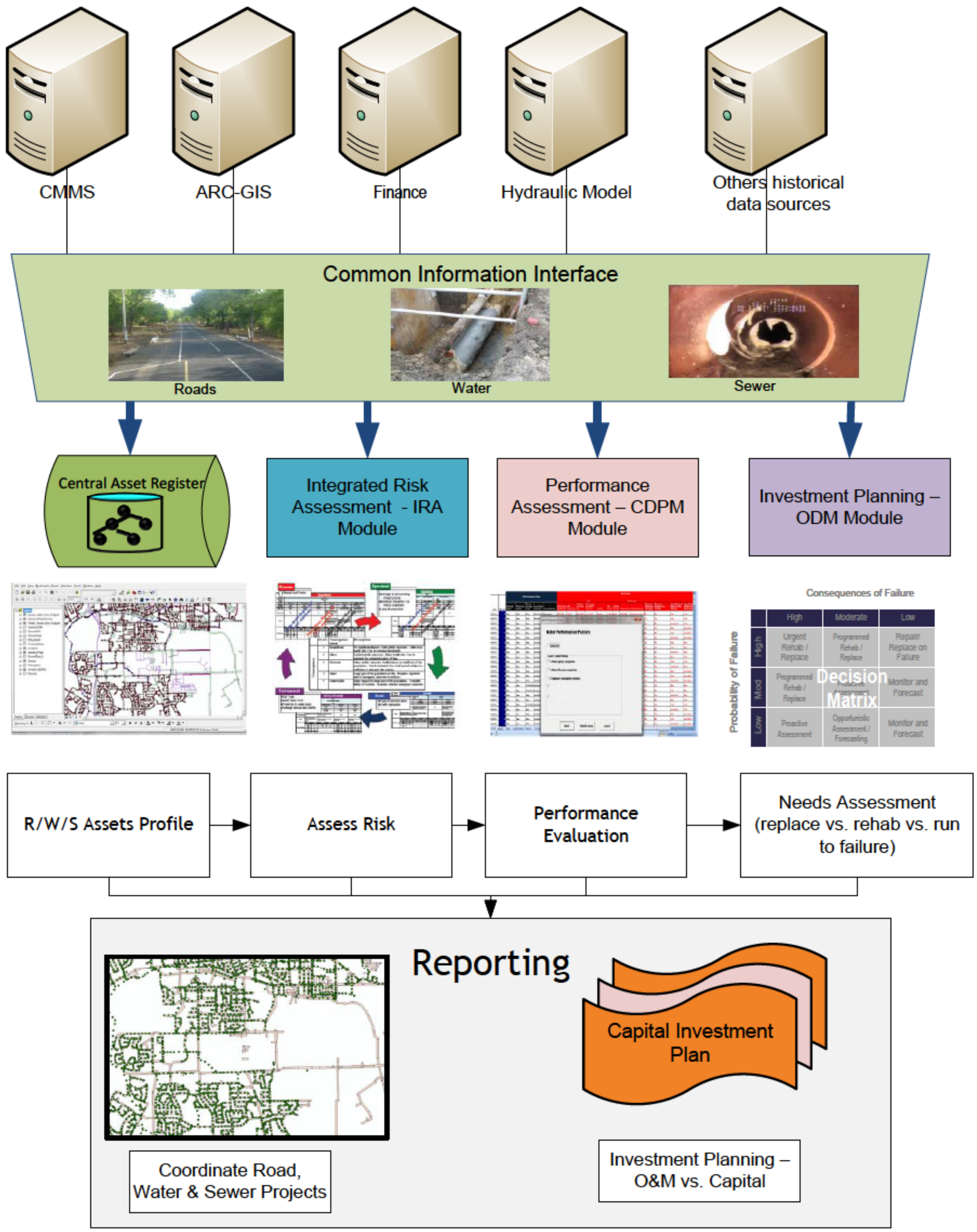


Figure 3-8 Integrated Decision Support System (IDSS) Architecture

As mentioned earlier this prototype integrates MS-Access, MS-Excel, Oracle and ESRI ArcGIS software and it is divided into the following three modules:

1) Integrated Risk Assessment - IRA module: assess risk index based on established probability & consequence of failure profile.

2) Performance Assessment- CDPM module; Calculate integrated client driven performance index using fuzzy membership function and historical record.

3) Investment Planning – ODM module: Identify projects for future capital investment using integer programming optimization.

After running all three modules, the results are presented in GIS to illustrate the areas of higher concerns in terms of risk, performance, and/or required investment. From this work, the final product, an effective and optimized capital investment plan can be generated.

CHAPTER 4: DATA COLLECTION

The data collection phase passed through three steps to collect the data required for the proposed models: (1) Select a case study, (2) Conduct data gap analysis, and (3) Conduct interview workshops/ questionnaire. These three phases of data collection were conducted over the various stages of the research.

The selected case study was from the city of Guelph, Ontario, Canada. The workshop interviews and questionnaires were conducted with municipal experts and consultants in (City of Hamilton, City of Guelph, Region of Peel, Region of Durham, City of North Bay, City of London, AECOM, and UEM). These workshops and questionnaires were designed to collect the opinions of practitioners regarding the main factors affecting the risk, performance indicators and business processes related to infrastructure management current practice.

4.1 Data collected for the Case Study

A case study from the city of Guelph, Ontario was set to evaluate and assess the developed integrated Decision-Support Framework for water, sewer and road network. The objective is to use the model to assess an integrated Infrastructure segment in terms of its performance, condition, risk, and optimization. The City of Guelph located in Southwestern Ontario, Canada, is roughly 25 kilometers east of Cambridge and 100 kilometers west of Toronto as shown in Figure 4-1. It has a population of approximately 115,000. The total operating budget is approximately $255 million with a capital budget of roughly $81 million.

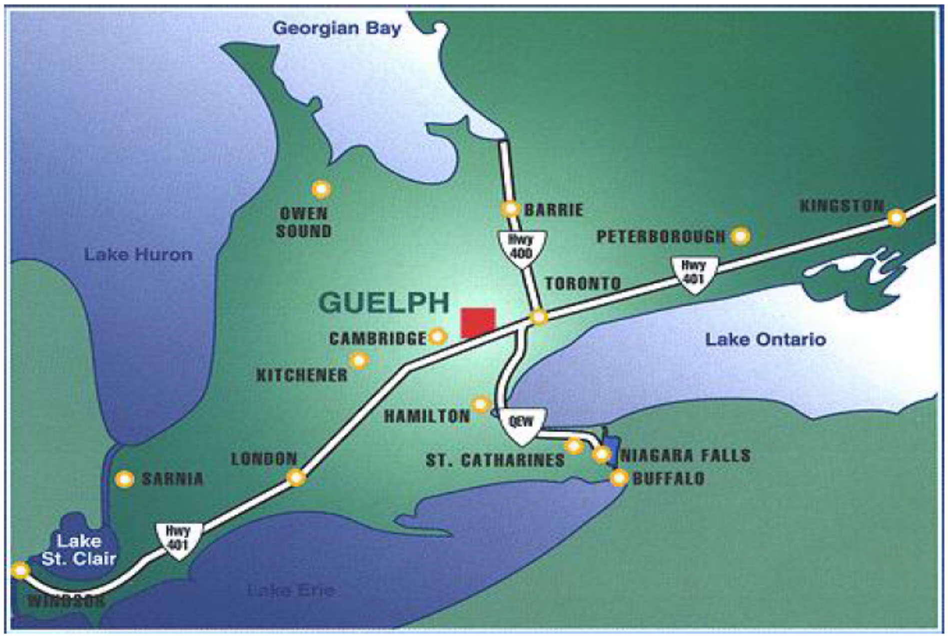


Figure 4-1 City of Guelph, Ontario Map

A review of the City's Asset Management Reporting Process was undertaken by conducting a desktop/background review, then an interview with major asset owners was carried out.

4.1.1 Data Gap Analysis Overview

In the initial data collection phase, a comprehensive list of documentation was requested from the City in order to provide the background and context to complete the data gap analysis. This initial data collection and review included data collection in several categories: Asset Registries; Various WAM (Synergen) generated reports, Capital Asset Prioritization System (CAPS) reports, Pavement Management System (PMS) reports , Water and Wastewater Cost of Sustainable Service reports, Auditing reports; Long Range Financial Plans; Business

Processes; Budgeting Procedures and Guidelines; and Development Charges Policies.

The data gap analysis phase was conducted based on information provided by the City. Analysis was done on the selected infrastructure asset classes (i.e. road segment, watermain and sewermains). The approach for conducting the data analysis relied on the following steps:

i. Analyze the main data elements for each asset class:

- *Asset Inventory*; is there reliable and complete lists for each infrastructure assets class?
- *Asset Condition*; is there reliable condition assessment information for each asset?
- *Performance Indicators*; is there consistent performance indicators reflecting the level of service being delivered (e.g. breaks for watermains)?
- *Asset Valuation*; is there an estimate of replacement value available for each asset?

ii. *Data Assessment:* an assessment of the current availability of asset inventory, asset registry, condition assessment, performance measures and valuation information is conducted. This assessment identifies:

- *Data format*; it identifies where data is stored and/or could be obtained (e.g. files, paper records, spreadsheets, databases, etc…)
- *Completeness*; it identifies how complete the records are (i.e. are they available for all individual Capital Assets or only a subset).

iii. *Priority:* A priority for acquiring the data was classified into one of three categories:

- *Immediate (Highest) Priority*: Data must be available before conducting the proposed integrated management framework.
- *Medium Priority:* Data is not necessarily required immediately for the integrated management but would be very useful for proper asset management. As such, the City should attempt to acquire this information as resources become available
- *Long-term (Low) Priority:* Data should be acquired as part of a long-term plan for achieving sound asset management practices

iv. *Data Gap:* This identifies the extent of missing data that needs to be collected. The level of data gap does not reflect the effort required in terms of data collection, only the discrepancy between what is needed and what is currently available. The extent of data gap was categorized as one of the following:

   a. *Large:* Absolutely no data is available
   b. *Medium:* Data is available for a portion of the asset inventory
   c. *Small:* Data is available for most of the asset inventory but small gaps need to be filled and/or all data is available but needs to be manipulated to suit integration management requirements
   d. *None:* All data records are available

4.1.2 Data Gap Analysis Results

The following sections present a summary of the Data Gap analysis task and the approach/assumptions that were used to bridge these gaps. Results are presented in a somewhat standard format to enable easy comparison between Asset classes. Table 4-1 shows valuation summary for each Asset.

Table 4-1 City of Guelph Infrastructure a Valuation Summary

Infrastructure Asset Category	Roads
Replacement Cost (2008)	~ $399.6 million
Total Length	~ 470 Km
No. of segments	~ 2800 segment
Infrastructure Asset Category	Watermains
Replacement Cost (2008)	~ $255.6 million
Total Length	~ 533 Km
No. of segments	~ 4275 segment
Infrastructure Asset Category	Sanitary Sewer Pipes
Replacement Cost (2008)[1]	~ $307.9 million
Total Length	~ 418 Km
No. of segments	~ 6850 segment

A sample of watermain data attributes is shown in Figure 4-2 , the figure shows four main tables as follows: "WaterMainData" which includes the main physical attributes for watermains such as (asset ID, age, material, size, etc.) this information is directly imported from GIS geodatabase. The other registry tables include "waterCondition", "waterPerformance", and "waterRisk", which include water condition, performance and risk related information respectively. These tables are linked via the watermain Asset ID field "OID_".

[1]Replacement Cost for Sanitary Sewers including laterals and manholes

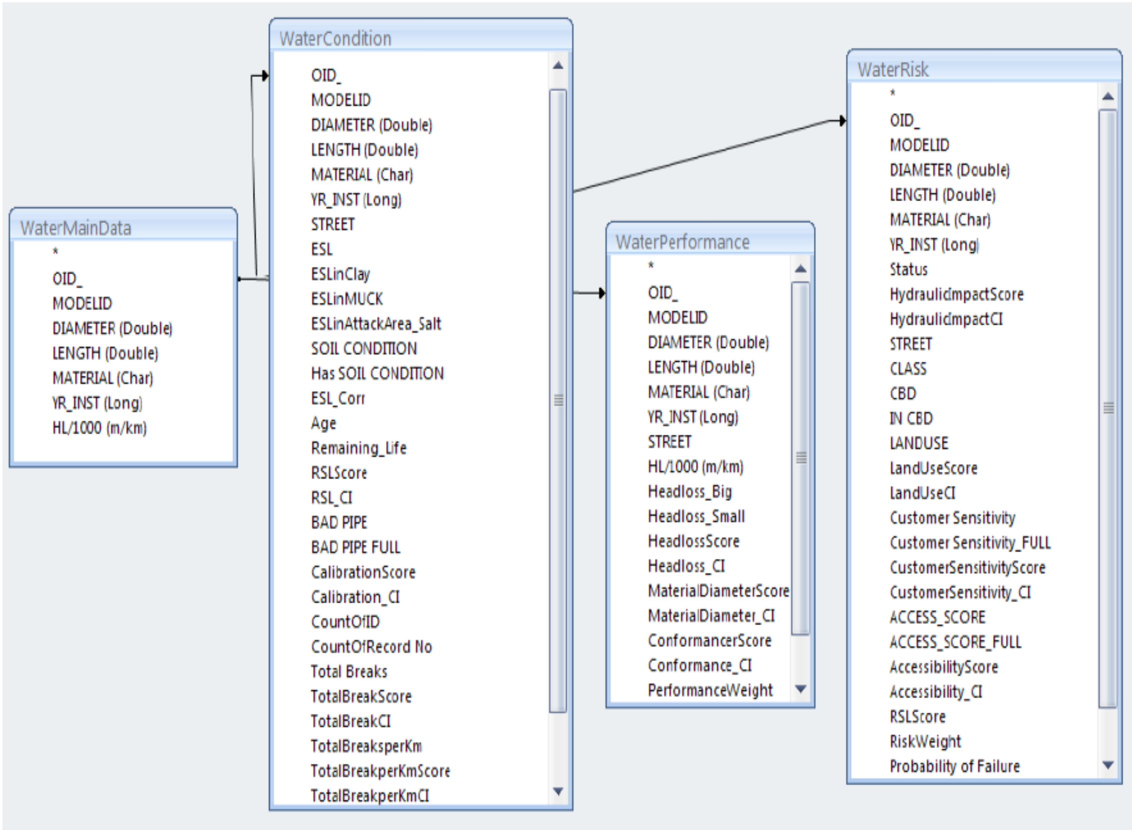


Figure 4-2 Watermains Asset Attribute Relationship

Table 4-2 presents data gap analysis results for watermains assets. The table below shows that minor data gaps exists for watermain Inventory record, for example less than 2% of inventory lacks material or diameter data. Valuation data are available in spreadsheets and hardcopy reports and are not stored in GIS; these data need to be linked to each asset in GIS. Performance data is limited to watermain break information and minor complaints tracking, other performance parameters need to be collected and stored in the correspondent registry tables. Risk data is available with small gaps; this data is stored in various databases.

Table 4-2 Watermains Data Gap Analysis Results

Data Type	Factors	Data Assessment		Gap	Priority	Comments
		Format	In -GIS			
Inventory		Available in GIS and Synergen, currently not a perfect 1:1 mapping of assets between systems	Y	Small	N/A	1% of inventory with unknown material type and 2% of inventory with unknown diameter. Assumptions to be made for valuation purposes
Valuation		Information available from Bill 175 report & PSAB 3150 report	N	None	N/A	
Performance		Break data, water quality (costumer feedback) is recorded	N	Medium	Immediate	Break records and physical condition of critical pipe would be a good start for performance tracking
Condition & Risk	Environmental Factors	data available from Transportation Services and Engineering Services in excel format	N	Small	Immediate	Type of Traffic/ Road, Type of Service Area are assumed complete, ground water level are partially available, and missing soil type for 95% of assets.
	Physical Factors	data includes: Pipe Diameter, Pipe Age, Material, etc are available in GIS	Y	None	N/A	
	Operational Factors	data includes: No. of breaks, Cathodic Protection, C-Factor, Operation Pressure, hydraulic capacity are available in excel and paper format	partial data available in GIS	Small	Long-term	C-factor is available in paper format only, it is recommended to convert to excel. Operation pressure values are not currently available
	Economic Factors	data includes: Pipe size, Pipe Shape, Pipe bury depth, contaminated soil, Low accessibility, pipe material, Land use, Road right of the way, and Road type are available in excel and GIS format	partial data available in GIS	Small	Long-term	contaminated soil area are not currently available

A sample of sewermain data attributes is shown in Figure 4-3, it shows four main tables as follows: "SewerMainData" which includes the main physical attributes for sewermains such as asset ID, age, material, size, etc. This information is directly imported from GIS geodatabase. The other registry tables encompass "SewerCondition", "SewerPerformance", and "SewerRisk", which include Sewer condition, performance and risk related information respectively. These tables are linked via the Sewermain Asset ID field "Asset_ID".

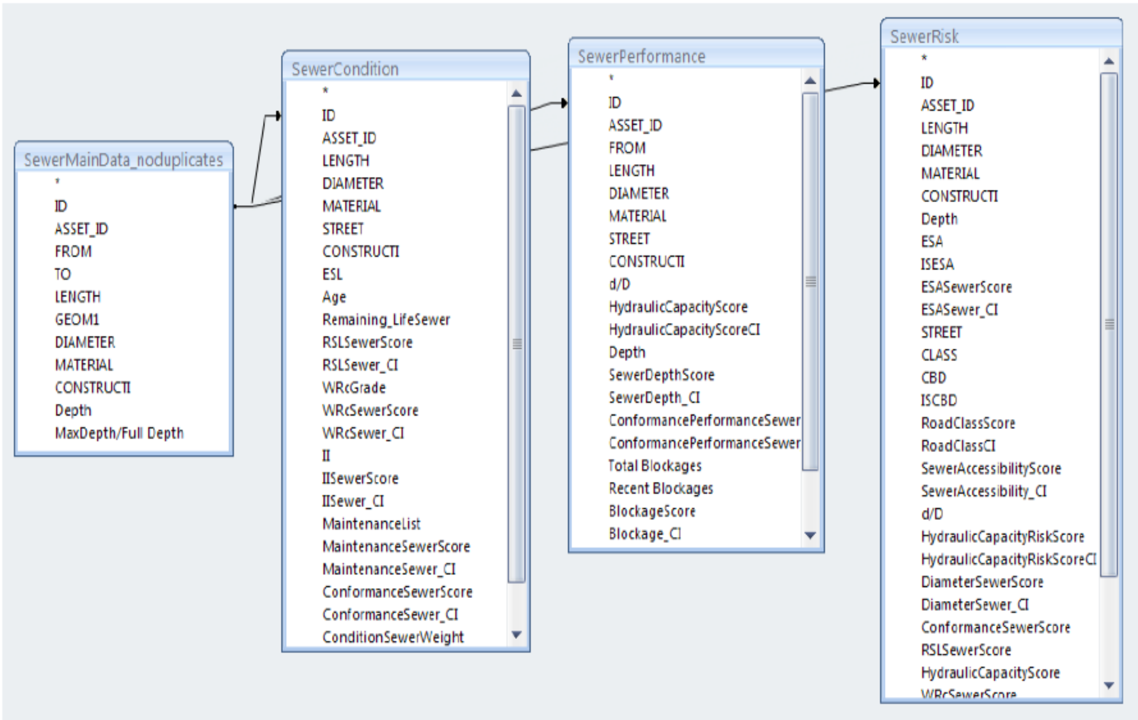


Figure 4-3 Sewermains Asset Attribute Relationship

Table 4-3 presents data gap analysis results for sewermains assets. The table below shows that small data gaps exists for sewermain Inventory record, for example less than 7% of inventory lacks material or diameter data. Valuation data is available in spreadsheets and hardcopy report and is not stored in GIS; these data need to be linked to each asset in GIS. Performance data is limited to basement flooding database and customer complaints database. The city started a program to assess the condition of its sewermains using CCTV in early 2008, the program intends to CCTV all sewermains within a three year interval. Data collected via CCTV were used for condition assessment and performance evaluation. Risk data is available with small gaps; this data is stored in various databases.

Table 4-3 Sewermains Data Gap Analysis Results

Data Type	Factors	Data Assessment		Gap	Priority	Comments
		Format	In -GIS			
Inventory		Available in GIS and Synergen, currently not a perfect 1:1 mapping of assets between systems	Y	Small	N/A	7% of inventory with unknown material type and 0.5% of inventory with unknown diameter. Assumptions to be made for valuation purposes
Valuation		Information available from Bill 175 report & PSAB 3150 report	N	None	N/A	
Performance		basement flooding and customer complaints is recorded. City-wide CCTV program currently being instituted,	N	Small	Long-term	
Condition & Risk	Environmental Factors	data available from Transportation Services and Engineering Services in excel format	N	Small	Immediate	Type of Traffic/ Road, Type of Service Area are assumed complete, ground water level are partially available, and missing soil type for 95% of assets.
	Physical Factors	data includes: Pipe Diameter, Pipe Age, Material, etc are available in GIS	Y	None	N/A	City-wide CCTV program currently being instituted, currently not all waste water asset have CCTV video but it is excepted to be completed by the end of 2010.
	Operational Factors	data includes: results of CCTV inspections	Y	Small	Long-term	
	Economic Factors	data includes: Pipe size, Pipe Shape, Pipe bury depth, contaminated soil, Low accessibility, pipe material, Land use, Road right of the way, and Road type are available in excel and GIS format	partial data available in GIS	Small	Long-term	contaminated soil area are not currently available

A sample of road data attributes include one main table and sixteen linked tables and is shown in Figure 4-4, it shows a summary of road asset attribute relationship. The main table "PvMainGeneral" includes the key physical attributes for road segment such as (asset ID, age, material, size, location, etc.) this information is directly imported from the city Pavement Management System (road- matrix). The other registry tables include road condition, inspections, traffic, events, etc. These tables are linked via the Road segment ID field "segment ID" and database index key field "PvMainGeneralOID". The risk and performance registry tables are stored in a separate database but they are linked via road "segment ID" field.

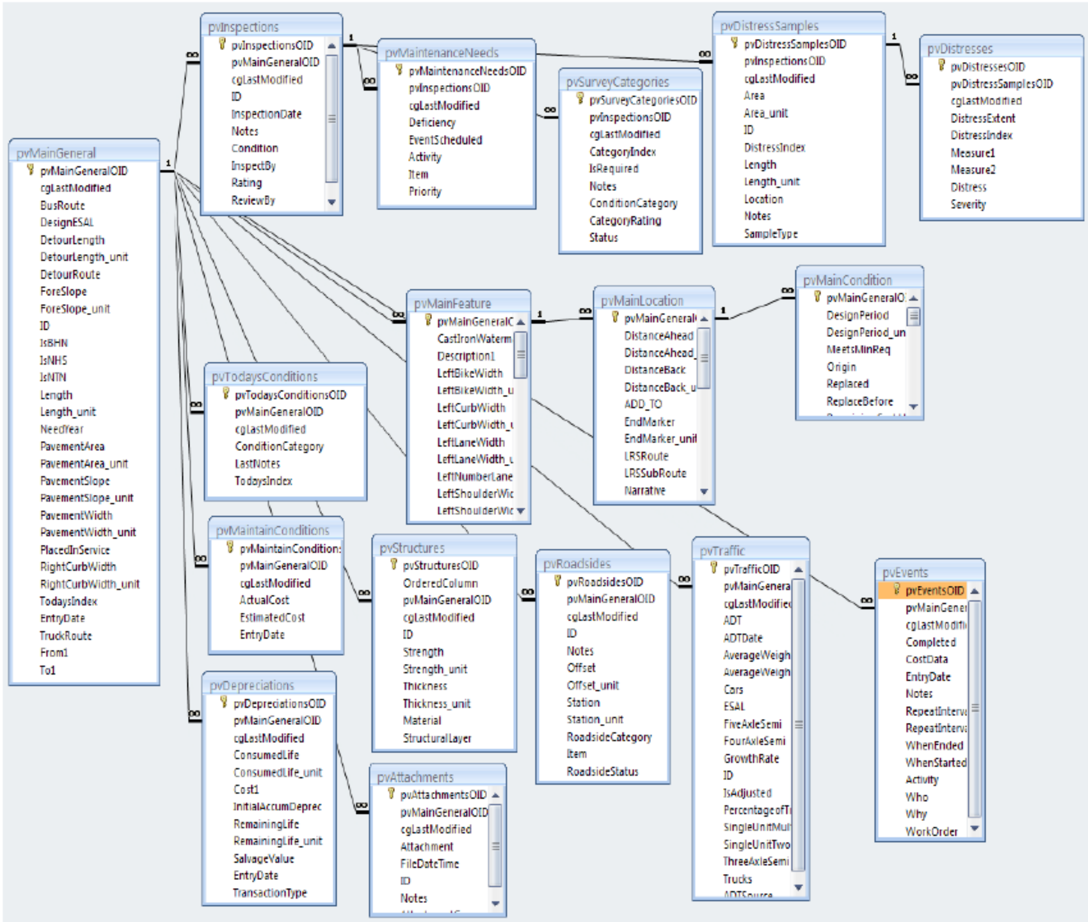


Figure 4-4 Road Asset Attributes Relationship

Table 4-4 presents data gap analysis results for Road assets. The table below shows that small data gaps exist for road Inventory record. Road data is stored in two main databases: 1) PMS- road matrix, and 2) GIS. These two databases don't match; there is inconsistency in the total number of segments. Valuation data is available in spreadsheets and hardcopy report and is not stored in GIS; these data need to be linked to each asset in GIS. Performance data is available in the pavement management system (road matrix). The city has an annual program to assess the condition of its roads in a three-year interval. Risk data is available with small gaps; this data is stored in various databases.

Table 4-4 Road Data Gap Analysis Results

Data Type	Factors	Data Assessment		Gap	Priority	Comments
		Format	In -GIS			
Inventory		Available in GIS and Synergen, currently not a perfect 1:1 mapping of assets between systems	Y	None	N/A	
Valuation		Information available for overall pavement structure split into pavement surface and road structure from PSAB 3150 report	N	None	N/A	
Performance		Pavement management system deteoration curves are available, need confirm the current level of service criteria	N	None	N/A	
Condition & Risk	Environmental Factors	data available from Transportation Services and Engineering Services in excel format	N	Small	Immediate	Type of Traffic/ Road, Type of Service Area are assumed complete, ground water level are partially available, and missing soil type for 95% of assets.
	Physical Factors	data includes: Road type, road class, installation date, etc are available in GIS	Y	None	N/A	City-wide Pavement management system program currently being instituted,
	Operational Factors	data includes: results of pavement distress inspections	Y	None	N/A	
	Economic Factors	data includes: contaminated soil, Low accessibility, road material, Land use, Road right of the way, and Road type are available in Pavement management system and GIS format	partial data available in GIS	Small	Long-term	contaminated soil area are not currently available

Data gap analysis key Observations:

- Asset registries are maintained with varying degrees of formality within all asset classes. Wastewater and roads perform condition assessment on a regular basis, while water assets are not evaluated regularly, or are evaluated on an ad-hoc basis.
- There is no centralized asset inventory, registry, hierarchy, information, knowledge from which it can effectively manage assets. The lack of information availability inhibits the ability to carry out efficient coordinated asset management. It is difficult to work with multiple inventories in multiple formats.
- The Capital Investment Programs and operational budgets are in place but there is no clear link to asset performance and priority. Additionally, it is not linked to the assessment of risks. Risk management frameworks vary by Asset Class.

4.2 Workshop Interviews and Questionnaire

The workshop and questionnaire process of this research was conducted in two stages. Stage I - (initial workshops) which encompass the research problem investigation, overview of current practices, and outlines the research methodology and selection of a case study. This phase was important to set the overall objectives and outline the time commitments required from each stakeholder. And Stage II- (advanced workshops) these workshops were specific to the model development (e.g. "weights" of the consequence of failure factors, and fuzzy membership functions development). The second stage of the workshops was in the form of interactive assessment of various factors and assessment of factors' contribution to the overall model development. Each of these workshops was accomplished in half a day with key representatives for each stakeholder group in attendance. The following list summarizes the total number of conducted workshops:

- Stage I workshops included two set of workshops
  - Workshop (No.1) - Problem statement, general presentation overview.
  - Workshop (No.2) Current practice assessment for Risk, performance, and optimized decision making.
- Stage II workshops included three set of workshops
  - Workshop (No.3) Risk factors detailed weighting and questionnaire
  - Workshop (No.4) Performance parameters weighting and membership function development

- Workshop (No.5) Integration of current practices & challenges, and optimization overview

Stage I- the initial workshops were conducted with City staff with representation from Engineering Services, Waterworks, Waste Water, Operations, and Finance departments. Questions and checklists were prepared in advance. Additional information was obtained in the open discussion as part of the interview. Additionally, this task aims to involve key stakeholders that use or input data into the road, water and sewer system. Stakeholder participation involved three different levels: Awareness, Needs assessment and implementation.

- **Awareness:** Stakeholders / workshop participants are made aware of the importance of key data items in driving the decision-making process. This ensures early buy-in into the research study and highlights recommendations. PowerPoint presentation is used to define problem statements, research objectives, the proposed model description, and the expected effort required through the process.
- **Needs assessment**: Stakeholders / workshop participants are engaged to gain a better understanding of their data needs, process constraints, and priorities.
- **Implementation:** gather any recommended modifications to the way integrated decision making is currently handled within each service area or department.

Stage II- The second stage of the workshops was in the form of structured presentation and questionnaires. Characteristics such as the "weights" of the consequence of failure factors, defining the risk/ performance factors, client driven performance model fuzzy membership functions were collected using this questionnaire that was discussed with each expert in the workshop interview. A selected group of stakeholders were asked to participate in a one-on-one interview or a group interview to answer these questions related to research model development.

The following groups were involved through the various stages of the data collection process, as shown in Table 4-5:

Table 4-5 Stakeholders and Workshop Participants

City / Region	Group / Division	Participant Title
City of Guelph	Engineering Services	• Manager Of Infrastructure Planning, Design & Construction • Infrastructure Coordinator
	Waterworks	• Waterworks Project Manager
	Waste Water	• Wastewater Services Project Manager
	Operations	• Coordinator, Service Performance & Development
	Finance	• Capital Asset Consultant
City of Hamilton	Capital Planning (Asset Management)	• Senior Project Manager • Infrastructure Programming Technologist • Asset Management – Project Manager, Subsurface Infrastructure • Infrastructure Technologist
	Water Distribution Construction & Operations	• Project Manager
	HANSEN Support Management	• Technologist
Region of Durham	Construction Management Services	• Project Manager
	Environmental Service Design (Asset Management)	• Project Engineer • Engineering Technician

City / Region	Group / Division	Participant Title
	Technical Support (GIS data analysis group)	• GIS Project Engineer • Operation Technician • Senior Technologist • Technologist
	Transportation Infrastructure	• Project Manager
Region of Peel	Corporate Asset Management	• Manager, Corporate Asset Management • Asset Management Advisor • Project Manager
City of North Bay	Engineering Services/ Finance	• Project Engineer • Manager of Accounting • Financial Services Intern
City of London	Corporate Asset Management	• Division Manager • Asset Management Specialist
	Water Engineering & Operation	• Water Engineering Manager • Water Engineer • Water Operation Manager • Operation Engineer
	Waste Water Engineering & Operation	• Waste Water Manager • Project Engineer
	Transportation	• Project Engineer
Consultant	AECOM	• Technical Director (Infrastructure Asset Management) • Practice Leader (Asset Management) • Project Manager (Asset Management) • Project Manager (water) • Project Engineer (Asset Management) • Project Manager (water & wastewater)
	Veolia	• Veolia Sewer Services Operation
	Stantec	• Project Engineer
	UEM	• VP Asset Management • Senior Project Engineer • Asset Management Leader

The two-stage process required over thirty workshops with various experts, some of which had to participate in three or more workshops (e.g. Region of Durham, City of Guelph, and City of Hamilton). Due to the limited availability of these experts, the duration of some of these workshops was shortened and/or integrated with other activities (e.g. Some of the City of Hamilton workshops were conducted as part of business process review workshops. In the Region of Durham the basis was on the data management project and the workshops in the City of Guelph were initiated as part of the TCA/PSAB initiative). Experts have provided a better understanding of the problem, needs, and the current practice in addressing corridor rehabilitation requirements. As a result, it has further enhanced the proposed methodology. The workshop and questionnaire process covers various study areas and allowed for obtaining advice on technical and operational issues of the proposed integrated decision support framework. A sample of the workshop material used is available in Appendix A.

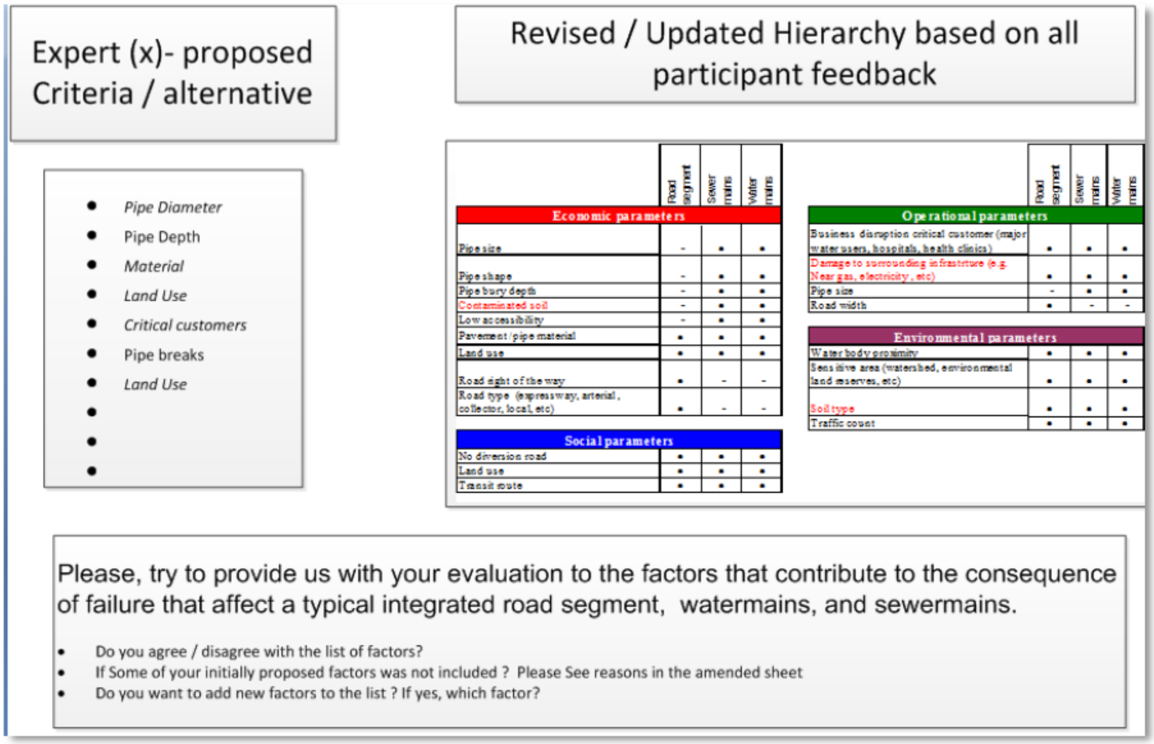
4.2.1 Risk Assessment Data Collection Process

The first task for each participant was to define a list of criteria and alternatives to represent the factors contributing to risk assessment, and performance evaluation for integrated corridor rehabilitation decisions. The experts were asked during the initial workshop to provide a list of factors and parameters that contribute to consequence of failure, probability of failure, and performance measure. For example, the following questions were asked to workshop participants:

- How do you address risk management in your division?
- What are your risk management priorities? Why?
- Are risk factors and/or modelling included in your data? What are these factors?
- How do you model your risk (example triple bottom-line)? Frequency?
- Do you have and can you quantify risk reduction strategies and costs?
- How are current risk exposures with regard to asset failures identified, evaluated and managed?
- Can and/or do you compare your risk information to other service areas?
- Is risk management assessment routine?

Feedback from over twenty experts from (City of Hamilton, Region of Durham, City of Guelph and AECOM consultant) was collected. The expert's participants were not concerned with the same aspects of the corridor rehabilitation problem, due to the diversity of their background and their area of expertise. The questionnaire participant had differed in their understanding of the problem, and therefore, they identified a diverse set of criteria and alternatives.

All identified criteria and alternatives were collated and summarized. Groups were then asked to evaluate the complete list of factors and provide feedback. Figure 4-5 shows a sample evaluation form that was circulated for evaluation. Once the feedback was received from various experts, then the second stage (II) of the workshops started by conducting a pairwise comparison matrix for each of those alternatives.



Expert (x)- proposed Criteria / alternative

- *Pipe Diameter*
- Pipe Depth
- *Material*
- *Land Use*
- *Critical customers*
- Pipe breaks
- *Land Use*
-
-
-

Revised / Updated Hierarchy based on all participant feedback

	Road segment	Sewer mains	Water mains
Economic parameters			
Pipe size	-	•	•
Pipe shape	-	•	•
Pipe bury depth	-	•	•
Contaminated soil	-	•	•
Low accessibility	-	•	•
Pavement /pipe material	•	•	•
Land use	•	•	•
Road right of the way	•	-	-
Road type (expressway, arterial, collector, local, etc)	•	-	-
Social parameters			
No diversion road	•	•	•
Land use	•	•	•
Transit route	•	•	•

	Road segment	Sewer mains	Water mains
Operational parameters			
Business disruption critical customer (major water users, hospitals, health clinics)	•	•	•
Damage to surrounding infrastrture (e.g. Near gas, electricity , etc)	•	•	•
Pipe size	-	•	•
Road width	•	-	-
Environmental parameters			
Water body proximity	•	•	•
Sensitive area (watershed, environmental land reserves, etc)	•	•	•
Soil type	•	•	•
Traffic count	•	•	•

Please, try to provide us with your evaluation to the factors that contribute to the consequence of failure that affect a typical integrated road segment, watermains, and sewermains.

- Do you agree / disagree with the list of factors?
- If Some of your initially proposed factors was not included ? Please See reasons in the amended sheet
- Do you want to add new factors to the list ? If yes, which factor?

Figure 4-5 Initial Criteria/Alternatives Evaluation Feedback Form

Next, each expert was asked to make pairwise comparisons between factors within the hierarchy. Analytic Hierarchy Process (AHP) uses pairwise comparisons to derive priorities or weights for each factor within the developed hierarchy (Saaty, 1980). AHP is integrated into a Delphi framework by repeating the AHP after the experts receive anonymous Feedback of the criteria and weights which were articulated by the other experts. With this feedback each assessor uses the AHP approach to reconsider his set of criteria, weighting and to repeat the weighting of the factors with the revised set of criteria. The AHP consistency checks was performed at two levels individual and group level, then a final weighting was established based on the group feedback.

The Delphi process achieves interaction among the members of a group of experts, with the feedback of the criteria and weights of other experts.

Individuals with different divisional perspectives contribute to each other's understanding of the issues involved in determining risk drivers and performance evaluation from a road, water and sewer perspective. With this process, individuals tend to redefine their criteria, and revise their weighting. Thus, they move toward a consensus as shown in Figure 4-6.

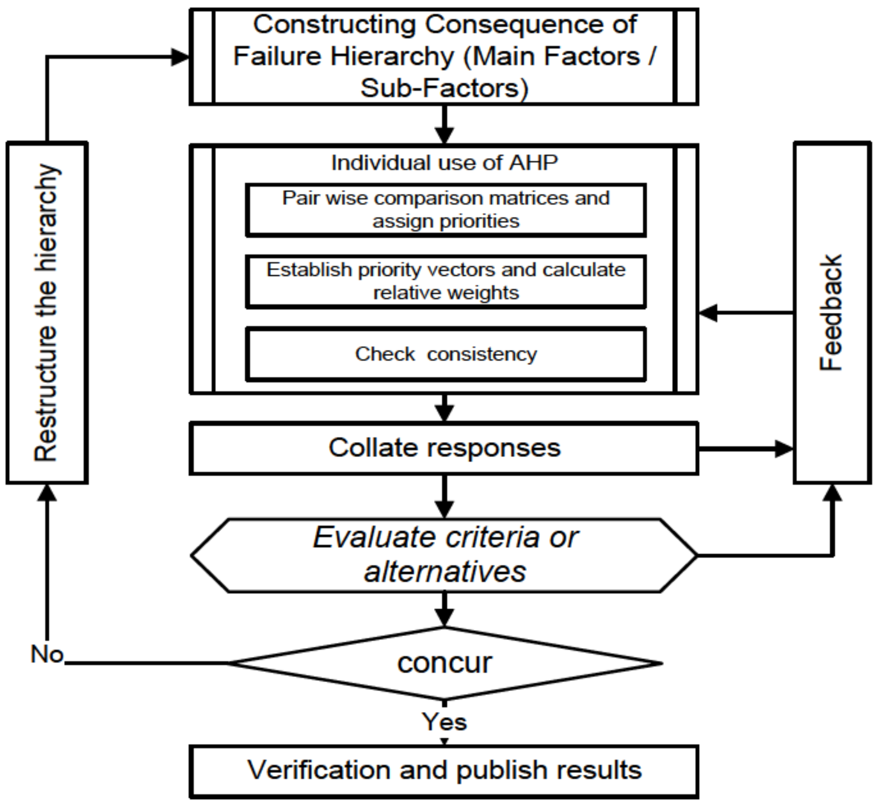


Figure 4-6 Delphi-AHP Consequence of Failure Model Framework

The above figure summarizes the step related to developing relation within the consequence of failure main factors / sub-factors through pair-wise comparison matrices (size n x n) that compare the main factors / sub-factors with themselves. Then the matrix is filled in with numerical values representing the relative importance or likelihood of each main factor/sub-factor. The final result provides the relative weights for each main factor/sub-factor on a scale out of 1.0 points.

Each main factor/ sub-factor weight represents the relative importance of this factor among the other factors. The outcomes of the initial evaluation are shared with the workshop participants to seek concurrence of the overall results and approach.

4.2.2 Client Driven Performance Data Collection Process

As mentioned earlier, each participant was to define a list of criteria and alternatives to represent the factors contributing to performance evaluation for integrated corridor rehabilitation decisions. The experts were asked during the workshop to provide a list of factors and parameters that relate to Client / Customer levels of service and performance measure. This step aims to define the key performance measures required for both customer and technical purposes. For example, the following questions were asked to workshop participants:

- What are the business activities
- Who are the relevant customers
- Have you defined any levels of service? What are they? Are any of your LOS legislated?
- Do you know what level of service your customers expect? Are those expectations met? How is this recorded? Do you survey your customers regularly?
- What are the factors that affect client / customer level of service?

Feedback from experts from (City of London, Region of Peel, City of Guelph, and UEM consultant) was collected. Additional information was provided by participants, for example Table 4-6 and Table 4-7 shows the key element of customer and technical performance measures currently utilized by the Region of Peel.

Table 4-6 Sample Region of Peel Public Service Performance Measure

Public Service View					
Program Descriptions		**Strategic Service Parameters**			
Program	**Service Name**	**Strategic Service Objective**	**Service Output**	**Customer Level of Service**	**Service Improvement Objective**
Water	Water Distribution	To provide the customers of Peel with safe, continous high quality drinking water at a practical cost.	Cubic Metre of Potable Water Delivered	Potable water at an acceptable pressure. Efficient and effective water service at the lowest practical cost.	Provide adequate water pressure to all system zones Enhance protection to the water distribution and transmission systems Reduce number of water main breaks Improve mitigation and management of power failure events

Table 4-7 Sample Region of Peel Internal Service Performance Measure

Internal Service View				
Asset Association		**Reporting Parameters**	**Other Treatments**	
Internal Service Name	**Asset Class Associated**	**Technical Level of Service (TLOS)**	**Standard Operating Parameters (SOP)**	**Maintenance TLOS and Design Standards**
Water Distribution & Maintenance	Distribution Mains	Maximum 5 breaks per km of pipe	Maximum 6 breaks per 100km per year (Whole Network)	
		Maintain a minimum pressure of 50 psi during maximum day demand periods		Design capacity to meet 40 psi during peak day demand, and 50 - 100 psi during Maximum Day demands. Minimum 300 mm diameter watermains for industrial and school land uses
	Small Feeder Mains (400-600mm)	Maximum 2 breaks per km of pipe	Maximum 1 break per 100km per year (Whole Network)	
		Maintain a minimum pressure of 50 psi during maximum day demand periods		Design capacity to meet 40 psi during peak day demand, and 50 - 100 psi during Maximum Day demands. Minimum 300 mm diameter watermains for industrial and school land uses
	Large Feeder Mains (750mm+)	Maximum 20 high tensile strands breaks per section	Acoustic monitoring once 10 high tensile strands breaks per section are identified through electromagnetic inspection	
		Alternate (until additional tensile strand data is available) - No Breaks		Use lifecycle curves, with an end of life of 80 years for current feedermain and transmission main inventory. Assume 150 years for new feeder and transmission mains, to reflect improved monitoring and preventative maintenance practices.
		Provide redundancy to supply average day demand during a failure event.		
		Maintain a minimum pressure of 50 psi during maximum day demand periods		Design capacity to meet 40 - 100 psi during Maximum Day demands within each zone.
		Not Required	Maximum velocity of 3 m/sec	Design the mains to maintain a velocity of 1 to 3 m/sec

Once the list of factors is defined the next stage (II) of the process is to establish ranges and develop a fuzzy membership function for each factor. Details of each membership function is covered in Section 5.2.3 Fuzzy Membership Functions. Next, each expert is asked to make pairwise comparisons between factors within the client / customer performance hierarchy. AHP uses pairwise comparisons to derive priorities or weights for each factor within the developed hierarchy.

4.2.3 Optimization and Decision-Making Data Collection Process

The optimized decision-making data collection passed through various stages as the research progressed. Initially the information gathering was associated with corridor rehabilitation, current practice and optimized decision-making approaches. The initial data collection was conducted via a one-on-one meeting with various groups (e.g. City of Hamilton, Region of Durham, City of Guelph, City of North Bay, Stantec and AECOM consultant). The information collected was limited to informal discussions with experts in order to understand current practice and apprehend the possible challenges that may transpire during the optimization process.

The second stage (II) was done via a structured workshop to get consistent feedback from participants. These workshops were conducted with (City of Hamilton, City of Guelph, and City of London). For example, the following questions were asked to workshop participants:

- What is the process for making integrated asset management decisions in your area?
- How do you decide whether to repair or replace your assets?

- Do you integrate water / sewer / road rehabilitation decisions? Do you utilize optimization? If yes, what is your optimization objective (e.g. minimize cost, maximize performance, minimize risk exposure, etc.)?
- Do you have processes in place, which enable future renewal costs of assets to be predicted, based on asset condition, performance and risk?
- Do you have any difficulties obtaining information from outside your division / department?

Results of these workshops allowed the development of the proposed optimization model discussed in Section 5.3 Optimization Model Development. Current practices varied from one city to the other and the current state of Asset Management of these cities also varied, which provided a better understanding of the problem and enabled the development of the solution. Once the optimization model is formalized the available data, from the case study, (e.g. inventories, condition, risk assessment, performance, financial information, etc.) was used to implement the proposed approach.

CHAPTER 5: INTEGRATED ASSET MANAGEMENT MODEL DEVELOPMENT

5.1 Integrated Risk Model Development

Using a risk-based approach helps to identify the importance of different assets in supporting the delivery of services (Asset Criticality). It also provides the ability to take into account the likelihood of asset failure and the associated consequences in terms of impacts on customers. The objectives of the proposed integrated risk model include:

- Applying proven risk management practices in decision-making process
- Understanding the criticality of the individual components of the asset
- Utilizing objective, repeatable methodologies, based on robust quantification, understanding of probability, impact to understand the risk of each asset and adjustment of interventions accordingly
- Producing Robust forecasts of the changes in the risk profile of asset base over time, enabling decision makers to determine the optimum level of capital and operational investments needed to sustain the assets.

Risk assessment, based on the objective assessment of the probability and consequences of asset failure, represents a practical and effective means of identifying and prioritizing capital and maintenance requirements. Although failure modes will differ, the risk dimensions should remain constant (Economic, Operational, Social and Environmental). Risk management framework is broken into three main steps as shown in Figure 3-5 and further discussed in details below.

5.1.1 Identification of Risk Factors

Risk Factors are a combination of qualitative and quantitative factors. Risks can be identified through a range of processes. Two approaches are used to conduct this step: (a) Literature review; and (b) Expert's opinion. Stakeholder interviews / workshops were used to identify current practice, issues and challenges, and confirm risk assessment objectives. Once risks are identified they are recorded in a risk register. As illustrated in Figure 3-5, risk events could be grouped into:

- ***Economic:*** Failure that result in class action lawsuits, regulatory fines, high repair costs, and loss of revenue
- ***Operational:*** Failure that result in functional, operational or maintenance inefficiencies, and could be due to under design or new requirements
- ***Social:*** Failure that result in service disruption that would impact customers
- ***Environmental:*** Failure of assets resulting in negative impacts to endangered or other species or habitats, to heritage resources, archaeological sites, water courses, aquifers, etc.

Understanding the above failure modes will allow an Asset Manager to understand and plan for the impacts of an event.

5.1.2 Consequence of Failure

Consequences of failure are a combination of qualitative and quantitative factors. Consequences of failure are linked to the asset types and include: Repair costs, loss of revenue, loss of service, loss of life, or injury, health impacts, damage to surrounding infrastructure or property, failure to meet regulation, third party losses, loss of image, etc. The parameters affecting cost of rehabilitation and replacement of R/S/W infrastructure assets were selected based upon four overall Criticality Indices as follows:

- ***Economic:*** effect of the asset's failure on monetary resources (e.g. repair costs, loss of revenue, etc.)
- ***Operational:*** effect of the asset's failure on operational ability (e.g. damage to surrounding infrastructure, loss of production, etc.)
- ***Social:*** effect of the asset's failure on society (e.g. loss of service, etc.)
- ***Environmental:*** effect of the asset's failure on the environment (e.g. health impacts, contamination, pollution, etc.)

Consequence of failure assessment methodology aims at transferring these qualitative and quantitative factors into a point system. Then develop a framework for the risk assessment by establishing a standard risk scoring system for various risk factors (Economic, Operational, Social, and Environmental factor Indices), and determine appropriate weighting for each risk factor based on their impact or consequence of failure (CoF). The establishment of risk indices, parameter scoring and weightings are based on expert opinion using a mixed

Delphi-Analytical Hierarchy Process (Delphi-AHP) approach. The Consequence of failure model can be formulated as in Equation 5-1.

$$CoF\ Index = \sum_{i}^{n}\sum_{j}^{m}[\boldsymbol{SW}ij * \boldsymbol{S.var}\ ij]$$

Equation 5-1

Where:

SW*ij* is the Overall Sub-factor Decomposed Weight for each Variable j within the index i (sum of all weights is 1)

$\mathbf{S_{Var\ ij}}$ is the score for each Variable j within the index i (scores ranges from 1 to 5 as shown in Table 5-1).

Table 5-1 Adapted Consequence of Failure Scale

Qualitative Consequence Scale		
Score	**Consequence Level**	**Description**
1	Insignificant	• No significant impact • Little or no public exposure • No impact to health risk • Can be tolerated indefinitely
2	Minor	• Limited public exposure • Minor health risk • Can be tolerated for an expected period of time
3	Moderate	• Minor public exposure • Health risk on small part of the population • Can be tolerated for a brief period of time (i.e. sufficient to plan and take action)
4	Major	• Large part of the population at risk • Requires expedient and/ or emergency measures to address
5	Catastrophic	• Major Impact for a large part of the population at risk • Complete failure of systems • Requires extreme emergency measures

Next, the parameters that influence each of the previous Criticality Indices were established and outlined as shown in Table 5-2. It is recognized that not all municipalities have access to the required data, as some of this information is administered by a third party (e.g. utility locations and soil types in some areas).

Table 5-2 Consequence of Failure Model Factors & Parameters

Factors	Road	Watermains	Sewermains
1. Economic Parameters			
Pipe Size (Diameter)	–	●	●
Road Size	●	–	–
Pipe Depth	–	●	●
Road Width	●	–	–
Material (Type of Pipe / Pavement Type)	●	●	●
Land Use	●	●	●
Accessibility	–	●	●
Road type / Class (i.e. Expressway, Arterial, Collector, Local, etc.)	●	●	●
2.0 Operational Parameters			
Business Disruption Critical Customer (i.e. Major Users, Hospitals, Fire Stations, etc.)	●	●	●
Hydraulic Impact	–	●	●
Pipe Size (Diameter)	–	●	●
Road Width	●	–	–
Damage to surrounding Assets (e.g. Near gas, Electricity, Cables etc.)	●	●	●
Sewermain Blockages	–	–	●
3.0 Environmental Parameters			
Water body proximity	●	●	●
Sensitive Area	●	●	●
Average Daily Traffic	●	●	●
Type of Soil	●	●	●
4.0 Social Parameters			
No Diversion	●	●	●
Land Use	●	●	●
Transit Route	●	●	●
Average Daily Traffic	●	●	●

*(i) Step 1: COF Variables Weights (SW**ij**):*

The establishment of risk weightings was a result of expert opinion using a mixed Delphi-Analytical Hierarchy Process (Delphi-AHP) approach as discussed in Chapter 4 above. After verifying the consistency of all matrices, weights (W_{indexi}) was established. The outcome of water Delphi-Analytical Hierarchy Process matrices are shown in Table 5-3:

Table 5-3 Consequence of Failure Main Factors & Sub-Factors Weights

Main Factor	**Sub-Factor**	**Weight ($W_{index\ i}$ & $W_{Var\ j}$)**	**Decomposed weight (*SWij*)**
1. Economic Index		**0.39**	
Economic	1.1 *Pipe Size (Diameter)*	0.19	0.0741
Economic	1.2 Pipe Depth	0.21	0.0819
Economic	*1.3 Material (Type of Pipe)*	0.16	0.0624
Economic	*1.4 Land Use*	0.06	0.0234
Economic	1.5 Accessibility	0.28	0.1092
Economic	1.6 Road type	0.10	0.0390
2.0 Operational Index		**0.27**	
Operational	2.1 Business Disruption Critical Customer	0.33	0.0891
Operational	2.2 Hydraulic Impact	0.18	0.0486
Operational	2.3 *Pipe Size (Diameter)*	0.16	0.0432
Operational	2.4 Damage to surrounding Assets	0.33	0.0891
3.0 Environmental Index		**0.21**	
Environmental	*3.1 Water body proximity*	0.18	0.0378
Environmental	3.2 Sensitive Area	0.47	0.0987
Environmental	3.3 *Average Daily Traffic (Road Class)*	0.24	0.0504
Environmental	*3.4 Type of Soil*	0.11	0.0231
4.0 Social Index		**0.13**	
Social	4.1 No Diversion	0.40	0.0520
Social	*4.2 Land Use*	0.10	0.0130
Social	4.3 Transit Route	0.20	0.0260
Social	4.4 *Average Daily Traffic (Road Class)*	0.30	0.0390
		Sum	**1.00**

Consequently, the decomposed weight of each sub-factor was calculated by multiplying the main factor weight by its sub-factor weight. This decomposed weight represent the overall weight of such sub-factor. Accordingly, priority can be established based on this overall weight as shown in Equation 5-2 as follows:

$$SWij = W_{index\ i} * \mathrm{W}_{\mathrm{Var\ j}} \qquad \text{Equation 5-2}$$

Where:

SW*ij* is the Overall Sub-factor Decomposed Weight for each Variable j within the index i (sum of all weights is 1)

$\mathbf{W}_{\mathrm{Index\ i}}$ is the weight for each Index i, (e.g. Economic Index, Operational Index, Social Index, and Environmental Index);

$\mathbf{W}_{\mathbf{Var\ j}}$ is the weight for each Variable j within the Index i (e.g. pipe size, depth, material, etc.);

Then the overall consequence of failure index (COF Index) can be calculated as shown in Equation 5-1 above.

(ii) Step 2: COF Variables Scores ($S_{Var\ j}$):

Each Consequence of Failure parameter has several variables / attributes in which they are not similar in their effect on consequence of failure. For example, pipe material sub-factor has various values, such as cast iron, steel, ductile iron, concrete, etc. These variables / attributes do not have the same impact on asset failure. Therefore, the effect of such variables / attributes is considered through the consequence of failure variable score term ($\mathbf{S}_{\mathbf{Var\ j}}$). Noting that the impact of these variables may differ from one municipality to the other, the presented COF variables scores were a result of group discussion of expert opinion from various municipalities. Variable intervals were discussed during the workshop, and scores have been applied accordingly.

Table 5-4, Table 5-5, Table 5-6 and Table 5-7 summarizes the sewermains variables / attributes scores, they show the economic, environmental, operational and social variables and attributes respectively. The watermain and road segment variables / attributes scores are available in Appendix B.

Table 5-4 Sewermain COF Economic Variables Scores (SVar j)

Factors	Score	Factors	Score
1.1 *Pipe Size (Diameter)*		***1.4 Land Use***	
Less or equal 300 mm	1	Agricultural	1
300 to 450 mm	2	Park / open space	2
450 to 750 mm	3	Residential	3
750 to 1200 mm	4	Commercial	4
Greater or equal 1200mm	5	Institutional	5
		Industrial	5
1.2 Pipe Depth		**1.5 Accessibility**	
Less or equal 2.0 m	1	Good	1
2.0 to 3.0 m	2	Marginal	3
3.0 to 3.5 m	3	Low	5
3.5 to 4.0 m	4		
Greater or equal 4.0 m	5		
1.3 Material (Type of Pipe)		**1.6 Road type**	
Poly Vinyl Chloride (PVC)	1	Local	1
Clay (CT, VC)	2	Collector	2
Asbestos Cement (AC, TRAN)	3	Arterial	3
Corrugated steel pipe (CSP)	3	Custom (e.g. University)	4
Metalic (STL, DI, CI)	4	Expressway / hwy	5
Concrete (RC)	5		
Concrete (HYPRES)	5		

Table 5-5 Sewermain COF Environmental Variables Scores (SVar j)

Factors	Score	Factors	Score
3.1 Water body proximity		**3.3 *Average Daily Traffic (Road Class)***	
Greater or equal 200 m away	1		
101 to 200 m	2	Low	1
51 to 100 m	3	Moderate	3
5 to 50 m	4	Heavy	5
Less or equal 5 m	5		
3.2 Sensitive Area		***3.4 Type of Soil***	
No	1	Non-Aggressive	1
Yes	5	Moderate	2
		Aggressive	3
		Highly aggressive	5

Table 5-6 Sewermain COF Operational Variables Scores (SVar j)

Factors	Score	Factors	Score
2.1 Business Disruption Critical Customer Low High (major users, hospitals, health clinics)	 1 5	**2.4 *Damage to surrounding Assets*** Low Medium High	 1 3 5
2.2 Hydraulic Impact d/D ≤0.5 0.5 – 0.65 0.65 – 0.75 0.75 – 0.85 d/D ≥0.85	 1 2 3 4 5	**2.5 *Sewermain Blockages*** Low Medium High	 1 3 5
2.3 *Pipe Size (Diameter)* Less or equal 300 mm 300 to 450 mm 450 to 750 mm 750 to 1200 mm Greater or equal 1200mm	 1 2 3 4 5		

Table 5-7 Sewermain COF Social Variables Scores (SVar j)

Factors	Score	Factors	Score
4.1 No Diversion No Yes	 1 5	**4.3 Transit Route** No Yes	 1 5
4.2 Land Use Agricultural Park / open space Residential Commercial Institutional Industrial	 1 2 3 4 5 5	***4.4 Average Daily Traffic (Road Class)*** Low Moderate Heavy	 1 3 5

Each Criticality Index was sub-categorized and weighted by a percentage multiplier that represents its relative importance among the other sub-categories. These Index Category weightings must add up to 100%. The variable score of each parameter consists of a point system that assigns a relative consequences importance score of 1 to 5 to each parameter value or group of values. Parameter Values can be a characteristic value or a Boolean Yes/No value that indicates whether the asset has the characteristic or not. A Parameter Value with a score of 5 would represent a major impact on a large portion of the infrastructure system while a score 1 represents no significant impact on current asset.

(iii) Step 3: Integrated COF Index

The process of calculating the integrated consequence of failure of a combined road, water, and sewer segment is simply the integration of the CoF_{Road}, CoF_{Water} , and COF_{Sewer} into one Overall CoF_{All} Index. Combining these indices in one Index was accomplished by developing self-organizing maps for clustering the CoF_{Road}, CoF_{Water} , and COF_{Sewer} via an unsupervised clustering technique. As mentioned before, each Index (CoF_{Road}, CoF_{Water} , and COF_{Sewer}) is divided into 5 grades (i.e. 1 to 5). They form a matrix of 125 different options; these options represent the CoF_{Road}, CoF_{Water} , and COF_{Sewer} Index of any integrated segment .Figure 5-1 shows a 3D graphic of the 125 different options.

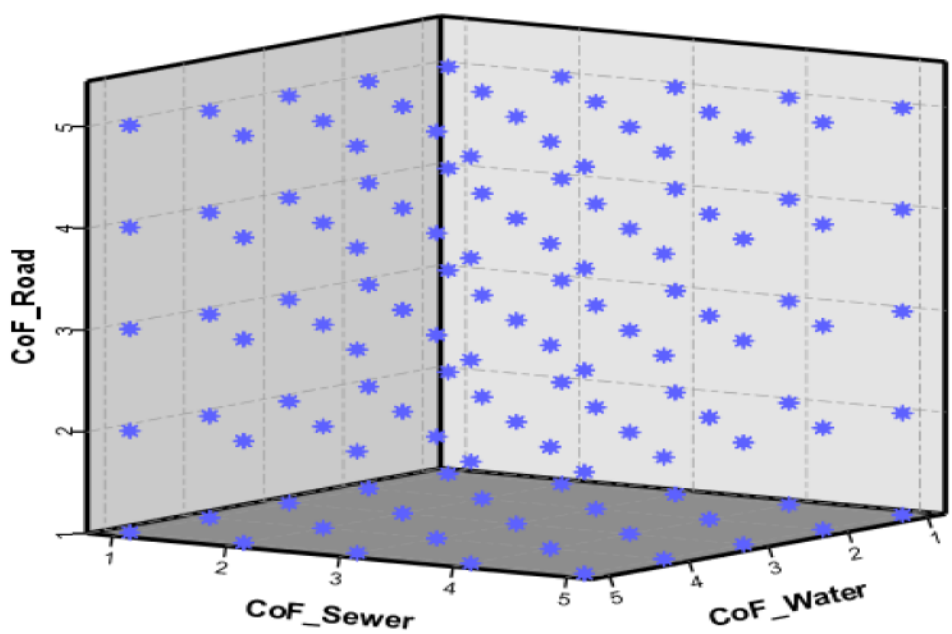


Figure 5-1 Integrated Consequence of Failure Matrix

Clustering software using clustering techniques such as the K-means is used for this purpose; the obtained transformed deduct values will be grouped or clustered into five categories of integrated consequence of failure classes. K-means is an unsupervised learning algorithm that solves the clustering problem. It is used to cluster objects based on attributes and break them into k partitions. The main theory is to define k centroids, one for each cluster. Then assign each object to a group to the nearest k centroid. When all objects have been assigned, recalculate the positions of the k new centroids. Repeat the previous two steps (i.e., allocate object to the new centroid, then calculate the new centroid). As a result of this loop, the k centroids change their location step-by-step until the centroids no longer move. In conclusion, this algorithm aims at minimizing the squared error objective function. The objective function is shown in Equation 5-3 (MacQueen, 1967).

$$V = \sum_{i=1}^{K} \sum_{xj \in S_i} \left| x_j - \mu_i \right|^2$$

Equation 5-3

Where $\left| x_j - \mu_i \right|^2$ is a distance measure between a data point *Si* and the cluster centre *μi,* is an indicator of the distance of the *S* data points from their respective cluster centers.

The K-means algorithm does not necessarily find the most optimal solution, corresponding to the global objective function. It is also sensitive to the initial randomly selected cluster centers, thus, it needs to be run multiple times to reduce this effect. Figure 5-2 shows a visual depiction of the initial clustering versus the final clustering example adapted from Moore (2001).

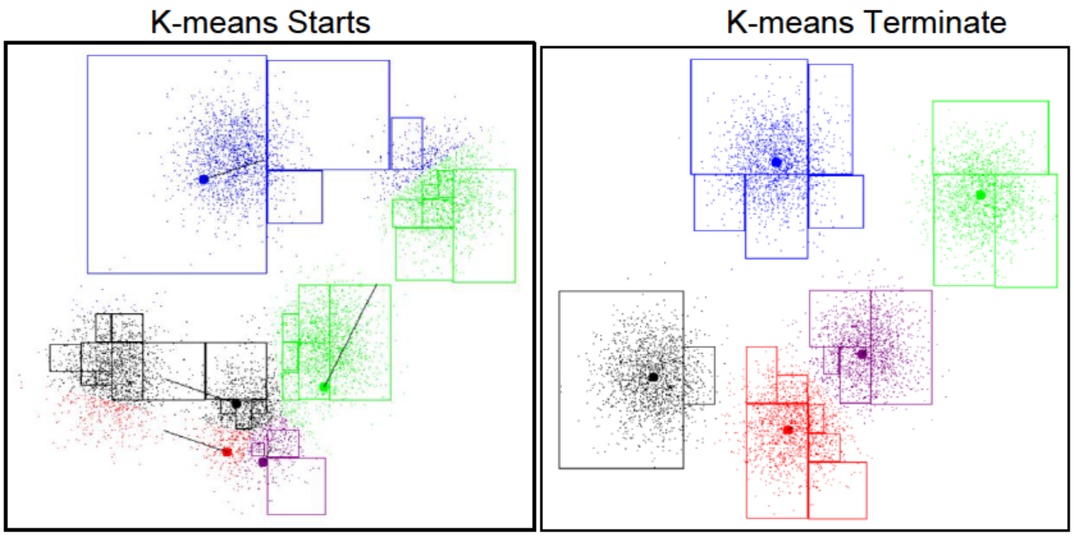


Figure 5-2 K-means Clustering Example

5.1.3 Probability of Failure

The likelihood of failure or probability of failure and failure modes will differ for each infrastructure asset (road, sewer and water segment). Independent infrastructure asset based condition rating and deterioration model is required in order to forecast future condition and current likelihood of failure. This step builds on the existing condition rating data and deterioration models available in literature, and current practices within the municipalities. The Probability of Failure (POF) Framework is shown in Figure 5-3 and POF score range from 0.01 to 1 as shown in Table 5-8.

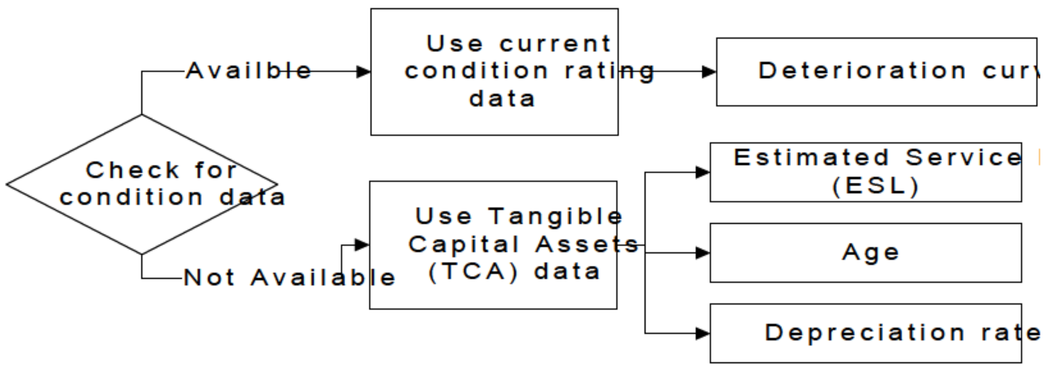


Figure 5-3 Probability of Failure Framework

Table 5-8 Probability of Failure (PoF) Scale

Probability of Failure (score range)	Probability of Failure (description)	Corresponding Condition Rating		
		Asset Condition	Remaining Life	Condition Rating Values
0.9-1	Almost certain	Very poor	All	Road: 0 <PQI < 30 Water/Sewer: 5
0.7-0.9	Highly likely	Poor	All	Road: 30< PQI < 45 Water/Sewer: 4
0.5-0.7	Likely	Fair/ Acceptable	<50 %	Road: 45< PQI < 65 Water/Sewer: 2-3
0.25-0.5	Unlikely	Fair/ Acceptable	>50 %	
		Good	<50 %	Road: 65< PQI < 85 Water/Sewer: 1- 2
0.01-0.25	Rare	Good	>50 %	
		Excellent- Very good	>50 %	Road: PQI > 85 Water/Sewer: 1

To determine the probability of failure, two main types of models can be utilized; namely, deterministic and / or simulation based. The deterministic approach utilizes the existing information related to asset age and / or condition using the table above to assign a probability of failure score to each asset. The simulation-based approach utilizes the historical repair data and conducts a correlation analysis with age and / or condition then assigns a standard probability distribution function (e.g. normal, beta, log normal, etc.) to predict the next failure interval. The proposed simulation based analysis is established using Excel spreadsheets and Decision Tools Suite by the Palisades Corporation as discussed in Shahata and Zayed (2013).

5.1.4 Overall Risk Index

Risk is the combination of the probability (likelihood) and consequence of failure for infrastructure assets to meet the objectives of the municipality. Risk management is an essential part of an overall asset management program. Every municipality that owns, operates, or acts as the approving authority for infrastructure assets will be exposed to some degree of risk. There are a variety of matrices that are used to combine probability and consequence to quantify risk levels. The risk model can be formulated as in Equation 5-4.

$$RI = POF \times COF \qquad \text{Equation 5-4}$$

Where,

RI: Overall risk index, range 0-5

POF: Probability of failure, range 0-1

COF: Consequence of failure, range 1 - 5

Implementation of the risk model requires building a meaningful, understandable relationship that combines probability and consequence to produce an index that enables risk levels to be compared. Figure 5-4 provides the adopted chart describing a numerical index of risk (hereafter called an overall Integrated Risk Index (RI).

			Consequence of Failure				
			Insignificant 1	Minor 2	Moderate 3	Major 4	Catastrophic 5
likelihood of failure	Almost certain	1.0	1.00	2.00	3.00	4.00	5.00
	Highly likely	0.8	0.80	1.60	2.40	3.20	4.00
	Likely	0.6	0.60	1.20	1.80	2.40	3.00
	Unlikely	0.4	0.40	0.80	1.20	1.60	2.00
	Rare	0.01	0.01	0.02	0.03	0.04	0.05

Figure 5-4 Risk Index Matrix

The proposed integrated risk assessment index scale as presented in Figure 5-9 extends from “0” to “5”, with “0” representing the Lowest risk exposure and “5” representing the extreme / highest risk exposure. The scale is divided into four levels (i.e. Extreme, High, Medium, and Low), adapted from scales that were used by IIMM (2011) and it was finalized after several discussions with Asset Managers and experts during the risk assessment workshops. The proposed risk index scale is color coded from green, represented a minor risk, to red, representing an extreme risk. This scale is also color coded to facilitate presentation in GIS.

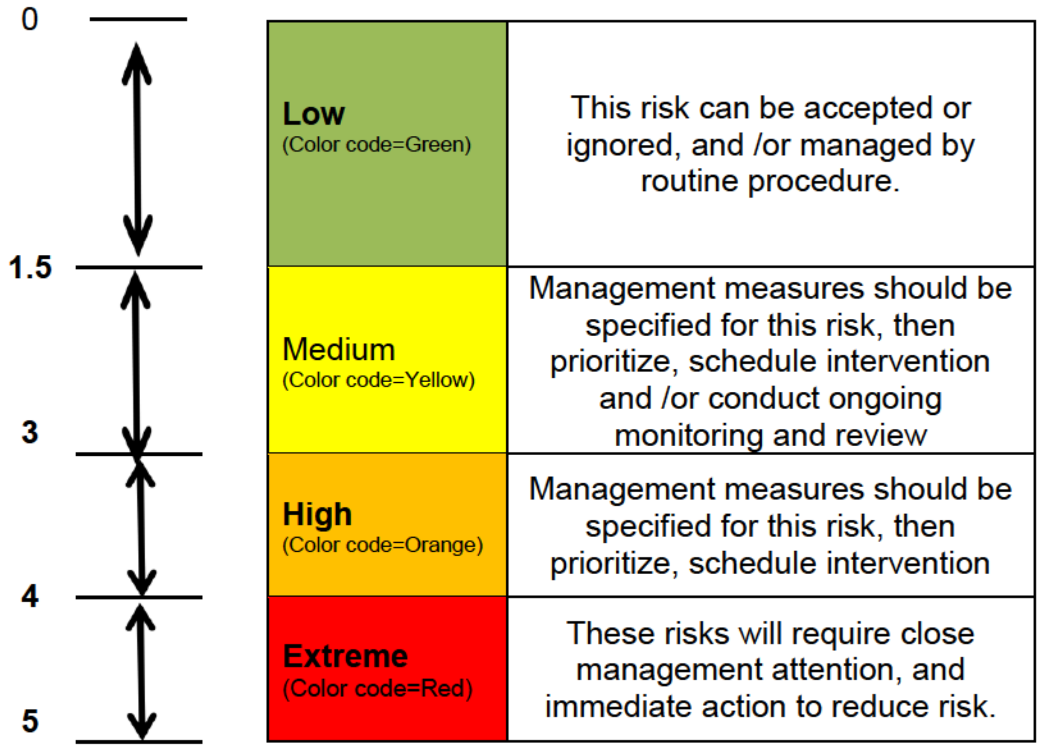


Figure 5-5 Integrated Risk Index Scale

5.1.5 Risk Mitigation Approach

Following completion of a risk assessment, there are a number of options to be considered with regard to managing the risk (i.e. avoid, transfer, reduce, or accept the risk). Risks can be addressed through the replacement, rehabilitation or upgrade of assets, and/or by the ongoing monitoring of risk and the development of contingency plans to minimize the consequence of a risk event. The risk ranking provides a basis to set trigger points to determine which risks may be discarded (minor) or identified as major and moderate risks. For example, the changes of colors from red to orange/yellow and from orange/yellow to green represent the risk tolerance levels of a municipality; different color tone zones trigger different actions:

- **Major risks (Extreme - Red)** - those risks with both a high probability of failure and a large impact. These risks will require close management attention, and immediate action.
- **Moderate risks (High/Medium - Orange/Yellow)** - are either likely to occur or have large impacts, management measures should be specified for this risk, then prioritize, schedule intervention and/or conduct a further review.
- **Minor risk (Low - Green)** - can be accepted or ignored;

Residual risk is defined as the projected risk after the mitigation action has been applied to the asset. Some mitigating actions are more effective than others, or some may have an excessive cost to move the asset to the minor risk (green) zone. For example, it may be more cost effective to reduce a major risk (red) to moderate risks (orange/yellow), by rehabilitating the asset as opposed to replacing it, or by changing operation and maintenance practices. It is unlikely that all assets will move to the minor risk (green) zone. An assessment of each project / alternative is needed to understand the level of residual risk following delivery of planned projects or changing operation and maintenance practices.

Major risk will require close management attention, and immediate action. There are two approaches for dealing with those major risks zones.

1. Rank the projects / assets in order of decreasing risk and then fund projects that address the highest risks. For example when working within an available funding limit, start at the highest risk project and work down the list until funds are exhausted) as shown in Figure 5-6

2. Following the development of solutions to address the risks, the Projects can be ranked by biggest risk reduction per dollar spent. Then, those projects that will give the largest overall movement in risk for a set funding allocation can be addressed as opposed to spending all of the available funding just mitigating the highest risks.

The second approach is recommended as it enables risk mitigation for larger number of assets while maintaining the same funding levels. This approach was utilized through the remaining implementation phases.

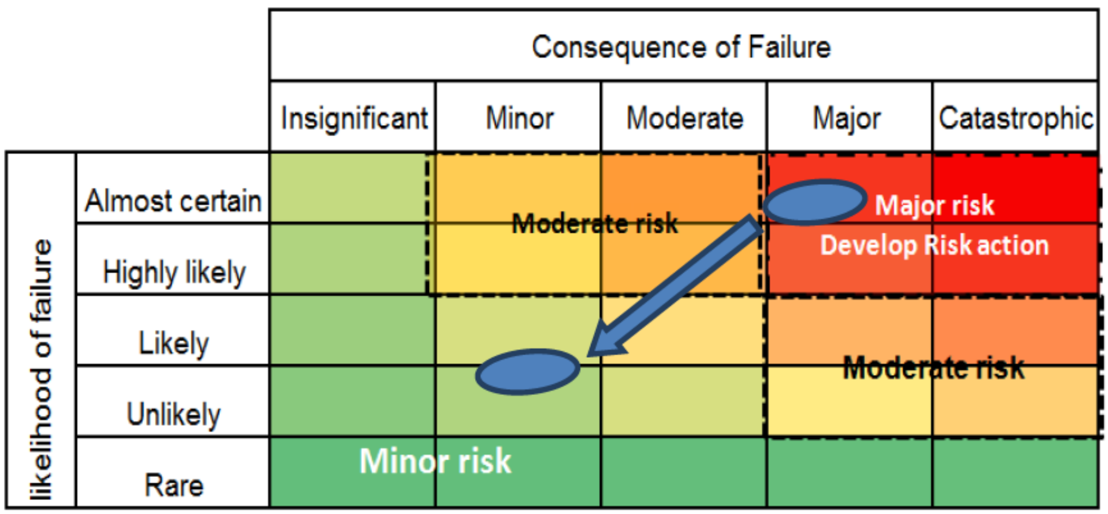


Figure 5-6 Asset Risk Evaluation Matrix

5.2 Client Driven Performance Model Development

The mandate of any Municipality is to deliver services to its customers. The extent to which these services are provided is defined through Levels of Service (LOS). These LOS need to establish reasonable expectations taking into consideration factors such as affordability and risk.

LOS can be measured at two levels:

- **Customer / Client** – defines the service that the Municipality/City provides to the Customer (e.g., supply of potable water of good quality, in sufficient quantity and with the fewest interruptions)
- **Technical / Asset** – defines the technical requirements to achieve the service objectives (e.g., watermain break rates)

Incorporation of Customer / Client Driven Performance Measures (CDPM) Index with Decision Support framework will aid municipalities in producing improved renewal plans in compliance with service standards, applicable codes, and regulations. Performance of the assets should be monitored regularly and adjustments made at the appropriate stages in an asset life cycle to achieve an acceptable balance between cost, condition, performance levels of service and risk. The CDPM model is developed using a combination of analytical hierarchy process (AHP) and fuzzy logic technique. The developed framework is then applied to calculate the CDPM index for the roads, sewer and water infrastructure assets. Figure 5-7 shows the CDPM index development and evaluation methodology which describes the steps required to establish

Customer / Client performance measures that can be used to evaluate the effectiveness of each asset / asset class:

a. Determine the performance and condition requirements of the infrastructure to ensure an adequate level of service is maintained over the long term.
    - Conduct a series of workshops and interviews to identify factors contributing to each asset class performance. Then identify performance target (e.g., minimum operating pressure of 50 PSI for watermain, can be used to track the performance of the water infrastructure).
b. Link customer level of service to asset level of service using service to asset diagram to summarize performance general parameters
c. Measure performance for each asset or asset class
d. Evaluate resulting performance measurements for each asset or asset class to confirm whether or not they meet the minimum performance targets
e. Utilize fuzzy membership function to link the key performance indicators to a current, minimum , and target (desired) level of service
f. Determine CDPM index

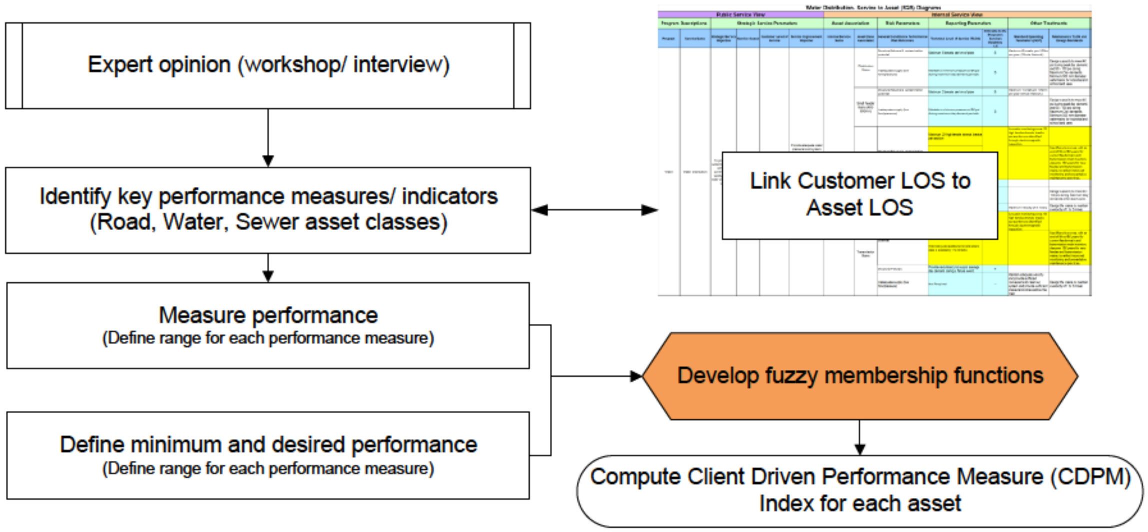


Figure 5-7 Client Driven Performance Measure (CDPM) Index Methodology

A standardized and consistent approach to the interviewing process was implemented to ensure that each group had a clear understanding of the research objectives and equal opportunity to contribute. A brief presentation was made at the start of each interview to summarize the research project background, and the relevance of the research project to the group being interviewed. Following the introductory presentation, the key performance indicators and membership functions were discussed and documented. The interviews focused on the specific asset class (i.e. water, road and sewer separately). The overall integration of road, water, and sewer CDPM index is done via pairwise comparison between the three asset classes to establish weights for each level of service criteria contribution.

5.2.1 Client Driven Performance Measures General Parameters

Client / Customer levels of service relate to how the customer receives the service in terms of both tangible and intangible measures. Client service levels may relate to customer satisfaction levels, level of customer complaints, etc.

Decision-makers and asset managers should plan, implement and control technical level of service in order to influence the client /customer level of service. The client /customer and technical dimensions are usually dependent on each other to the point that high technical LOS contributes to high customer service quality and vice versa.

The development of performance measures is fundamental in describing the required outcome in terms of operations, maintenance and rehabilitation needs of assets. Table 5-9 below includes examples from the Ontario Municipal Benchmarking Initiative (OMBI) performance measures that was developed for road, water and sewer infrastructure (OMBI, 2010).

Table 5-9 Roads, Water and Sewer Performance Measure

Performance Measure	**Typical / Acceptable Range (Low - High)**
Roads	
Riding Comfort Index (RCI)	70-100 RPI
Response time (Pothole repairs)	1-3 days
Skid resistance	0.2-0.3 (SCRIM)
# Accidents/year / Capital	Varies
Travel time/ intersection delays	Varies
# crack seal /km/ year	0-7
Water	
Response time: Emergency Minor leak	1hr - 4hr 1 day - 3 days
Duration of interruption	4 hr -12 hr
% Hydrant meeting fire fighter requirement	95%- 100% of all hydrant
Annual water quality Complaints/ 1000 people	Typical (0-2) - max. 12 Complaints
Annual water Pressure Complaints/1000 people	Typical (0-1) - max. 4 Complaints
Number of segment interruption	Typical (0-20) - max. 75 Interruptions
Number of boil water advisory days	Typical (0-1) - max. 20 Days
Number of watermain breaks per 100 km	7-12
Sewer	
Response time : Emergency Minor overflow	1hr - 4hr 2 hr- 6 hr
Annual number of sewermain backups per segment of sewermain	0-2
Blockages/ useful life of sewer	None - 10
Capacity issues (Number of overflows)	<1 in3yrs - <1 in5yrs
Time to clean up overflow	8hr - 24 hr

CDPM Index Factors Incorporated in the Model

In this step, the Performance measure factors are selected. Nine performance measure factors (two for roads, four for water, and three for sewer) are incorporated in this model, which represents the customer driven performance factors. These factors were supported by OMBI performance measure lists as shown in Table 5-9 above. The factors that were chosen to be incorporated in this model are selected by workshop participants based on the most understandable factors by customers and data availability . Other factors may be included in the future depending on the ease of gaining the required data for the additional factors by asset managers.

The factors that were selected to be incorporated in the CPDM model are shown in the figure below. The proposed fuzzy model structure consists of three branches (models) which correspond to each asset type (i.e. road, water and sewer), the results are then combined using the Analytical Hierarchy Process (AHP) to produce integrated CDPM Index as shown in Figure 5-8. The overall CDPM index is combined using a developed weights for road, water and sewer CDPM index.

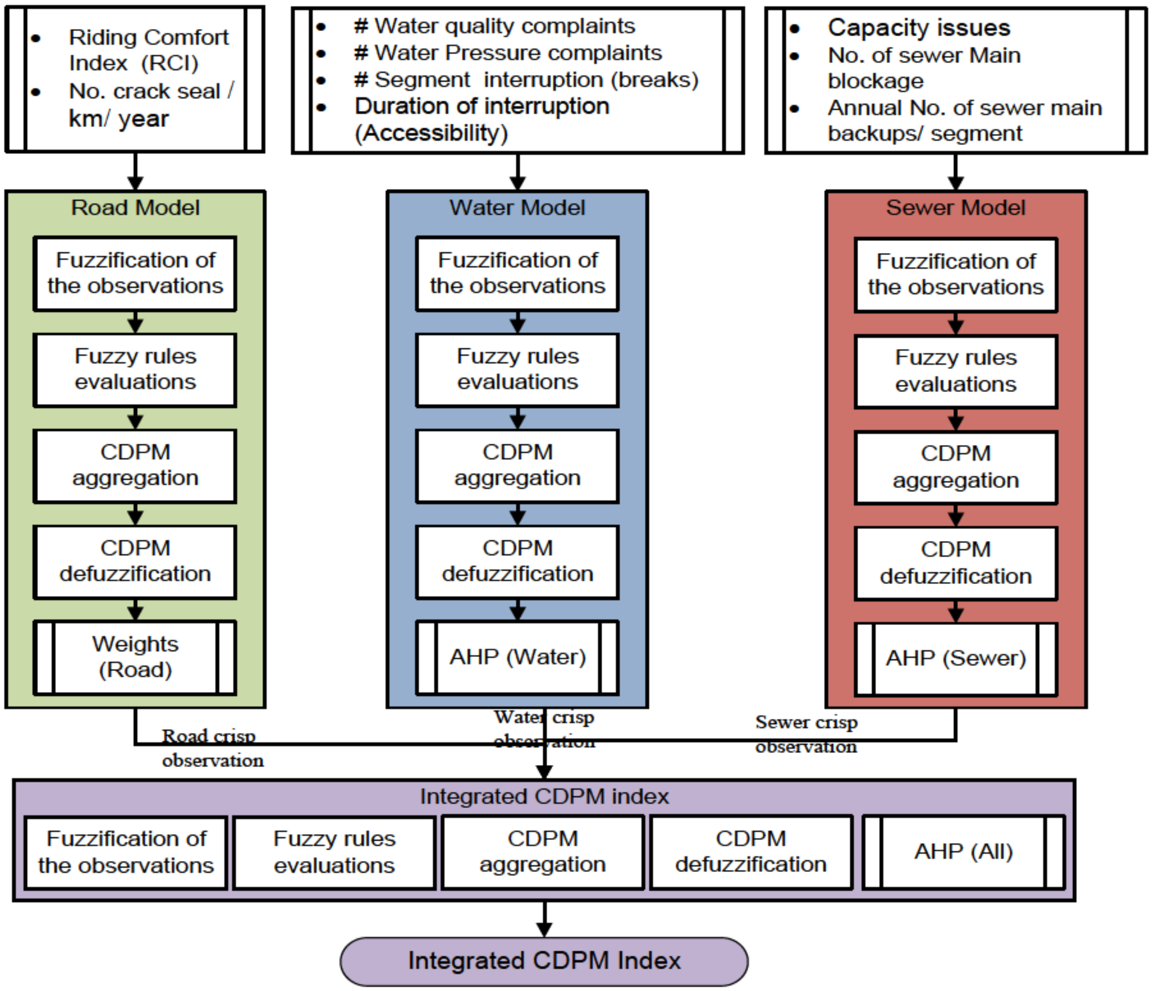


Figure 5-8 CDPM Model Component

5.2.2 Client Driven Performance Measures Index Scale

The next step is to set a CDPM index scale, which is used to assign a value that represents the category performance. This scale is used to represent the numeric values related to the linguistic representation. The proposed performance index (CDPM) scale as presented in Figure 5-9 extends from “0” to “10”, with “0” representing a very good performance and “10” representing a very poor performance. The scale is divided into five levels and adapted from several scales that were used by Al Barqawi and Zayed (2008), Shahata et al. (2008), Fares and Zayed (2009) and Fares, et al. (2012), it is then finalized after several discussions with Asset managers and experts during the workshops.

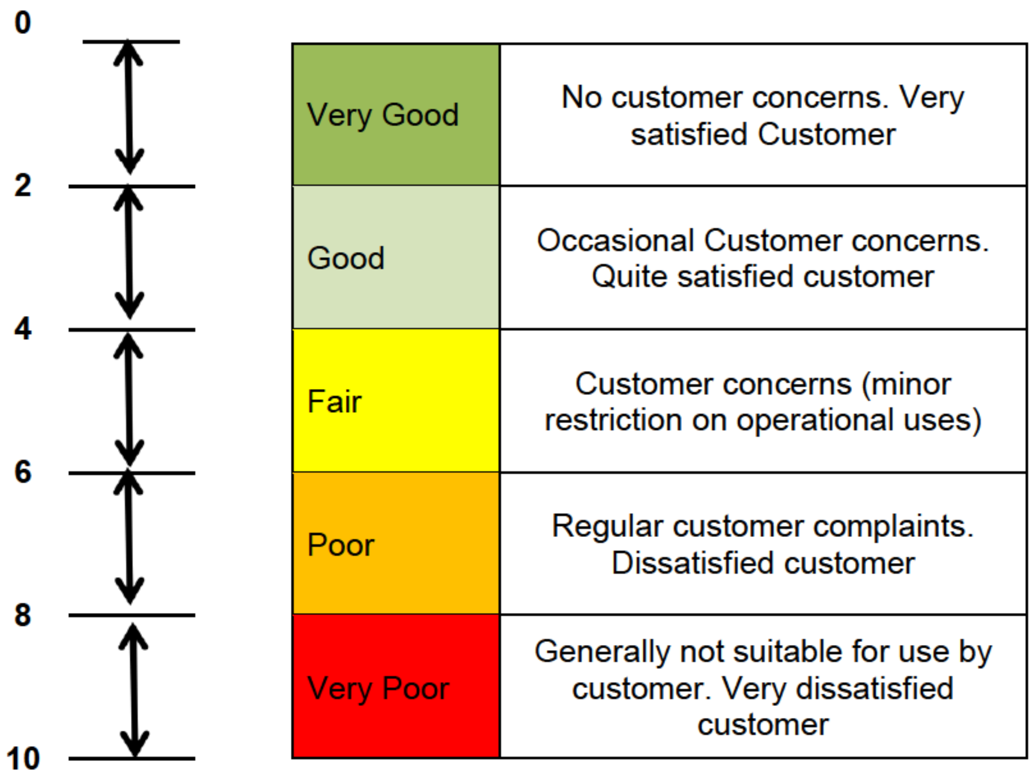


Figure 5-9 CDPM Index Scale

5.2.3 Fuzzy Membership Functions

The membership functions of the different performance measure factors are developed based on the information gathered from workshop participants and the literature, such as the characteristics of each factor, and the effects of these characteristics on the performance of each asset class. The performance measure factors are evaluated on a 0-10 scale and assigned a standard five membership function. The established fuzzy membership for each performance measure factor is summarized below:

(i) Water CDPM Model

Water CDPM model includes water quality complaints, water pressure complaints, segment interruption (breaks), and average duration of interruption.

Water Quality Complaints

Flushing, main breaks, construction of new mains, or from high demands on the system (such as in the morning or early evenings, fire fighting, outdoor water uses during the summer months) may upset the water system and result in dirty, discoloured, smelly, or cloudy water. A water quality complaint involves investigation of all customer calls requesting information on water testing and treatment practices or water quality test results or reporting concerns with water quality due to abnormal odour, colour or taste. Some municipalities do not link their water quality complaints to specific assets, then a spatial analysis may be required to allocate these complaints to the associated asset. For example, call center data can be utilized to spatially allocate the number of water quality complaints to various zones of the city. The number of complaints is then allocated to each watermain segment within this zone using GIS spatial analysis. The membership functions and their characteristics are shown in Figure 5-10. The data type to be used for this performance measure factor is the number of annual water quality complaints ranging from 0 to 20 where 0 indicates the best customer performance zones and 8 or more indicates the worst customer performance zones.

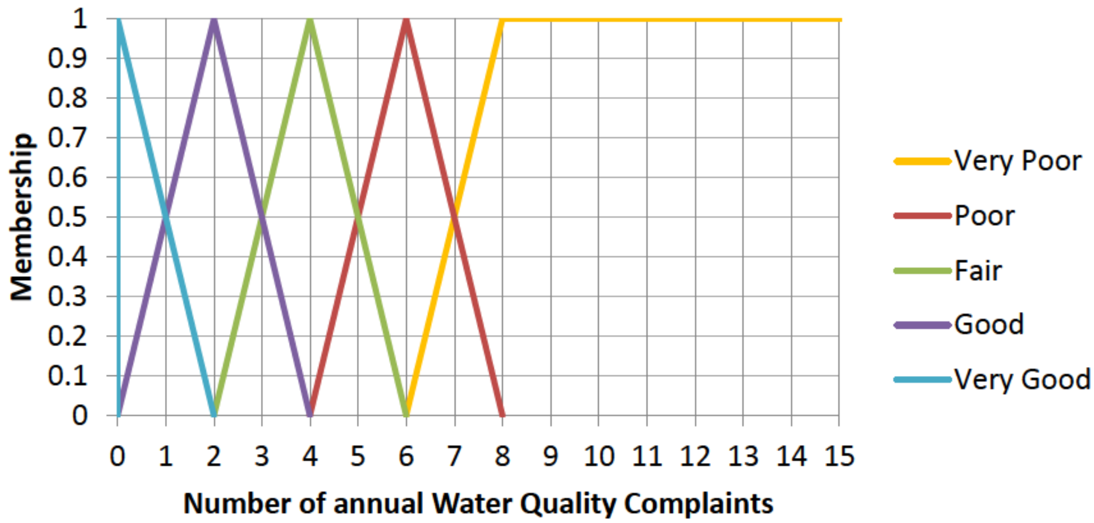


Figure 5-10 Water Quality Complaint Membership Functions.

Water Pressure Complaints

Low pressure can have a number of causes. For example, during high demands on the system (fire fighting, outdoor water uses during the summer months). Other causes of low pressure can include (inadequate pumping facilities; watermains that are too small, reduced pressure from the watermain because of leakage, equipment failures or blocked watermains). Some municipalities do not link their water pressure complaints to specific assets, then a spatial analysis may be required to allocate these complaints to the associated asset. For example, call center data can be utilized to spatially allocate the number of water pressure complaints to various zones of the city. The number of complaints is then allocated to each watermain segment within this zone using GIS spatial analysis. The membership functions and their characteristics are shown in Figure 5-11. The data type to be used for this performance measure factor is the number of annual water pressure complaints ranging from 0 to 7 where 0 indicates the best customer performance zones and 4 or more indicates the worst customer performance zones.

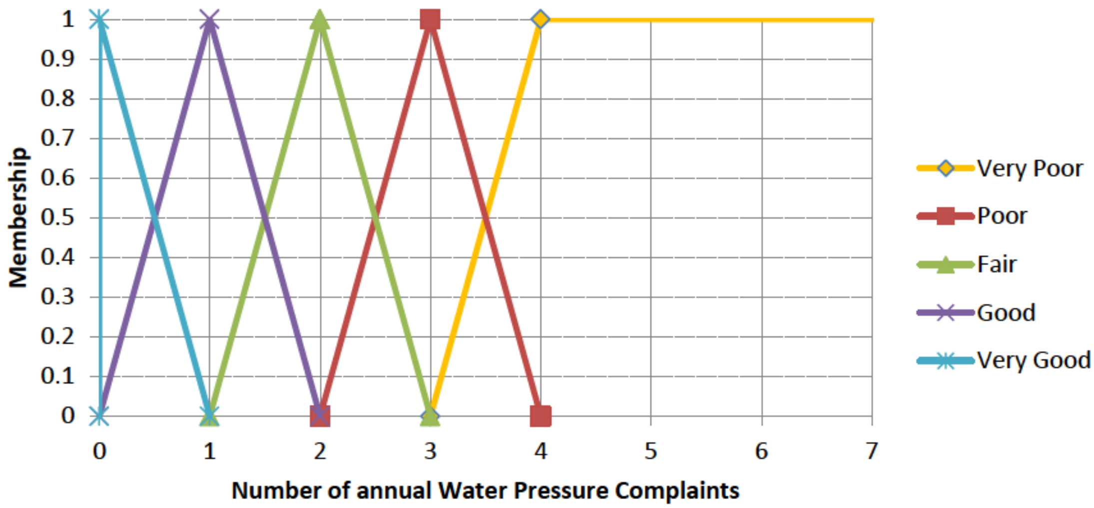


Figure 5-11 Water Pressure Complaint Membership Functions.

<u>Water Segment Interruption (Breaks)</u>

Water Segment Interruption or Watermain breaks are the leading indicator of a watermain's condition. They are the single highest factor in maintenance costs and service disruption. Performance is linked to the number of breaks during the life of the asset. A shape file containing break data is usually recorded by the municipalities or the breaks are sometimes attributed to mains inventory database. The membership functions and their characteristics are shown in Figure 5-12. The data type to be used for this performance measure factor is the number of water segment interruption (breaks) ranging from 0 to 15 where 0 indicates the best customer performance zones and 8 or more indicates the worst customer performance zones.

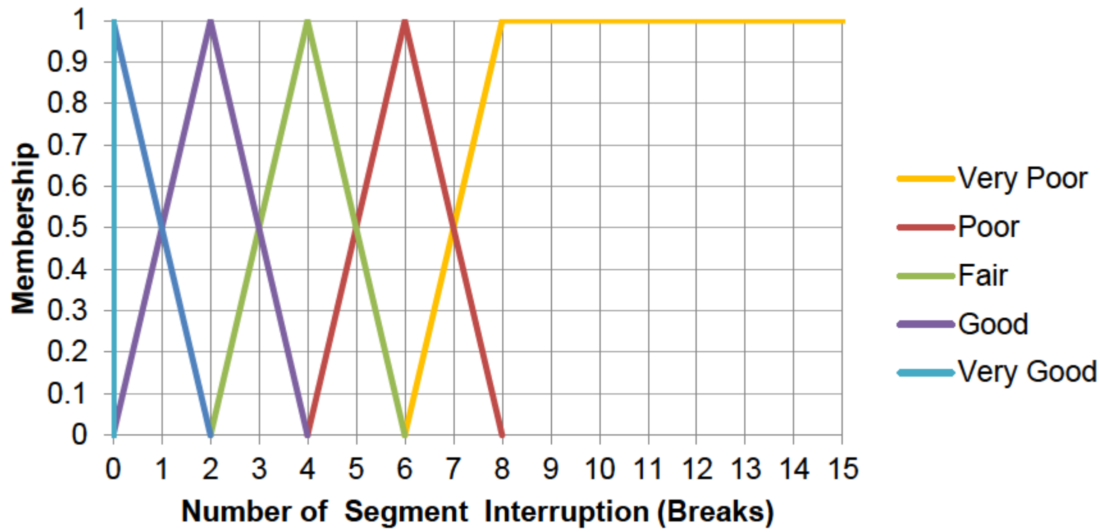


Figure 5-12 Water Segment Interruption (Breaks) Membership Functions.

Duration of Interruption (Accessibility)

In the event of a failure, limited access to infrastructure seriously hinders efforts to repair or isolate a problem. Extra time and resources would be required allowing the problem to potentially cause further damage to property and disrupt service. Areas where accessibility to infrastructure may obstruct corrective measures include, narrow or no easements, deep infrastructure, difficult or limited vehicle access. The membership functions and their characteristics are shown in Figure 5-13. The membership functions of the Duration of Interruption (Accessibility) are discrete and a 0.95 confidence level (certainty) is assumed. The data type to be used for this factor is linguistic and chosen from this list: good accessibility, marginal accessibility, and low accessibility.

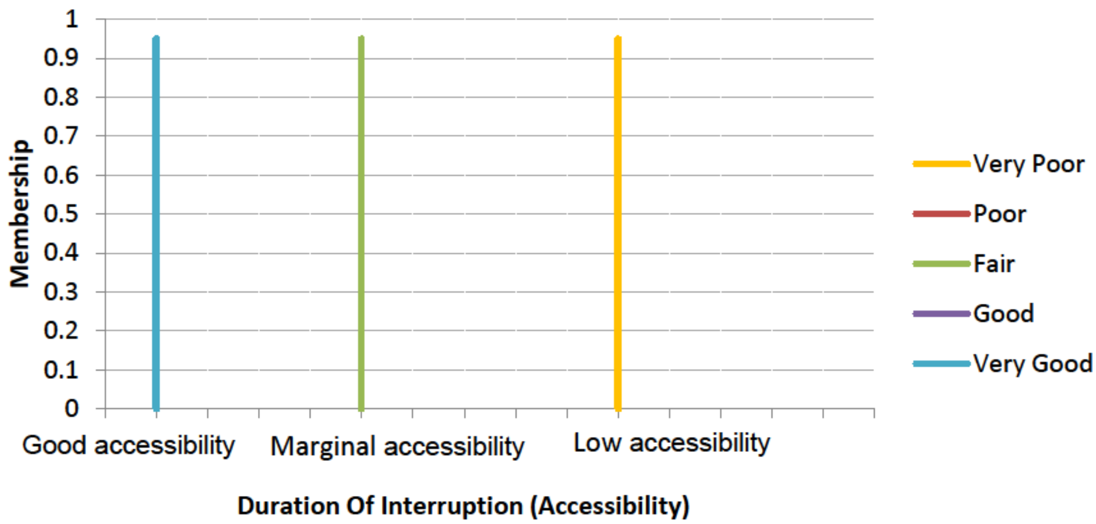


Figure 5-13 Duration of Interruption (Accessibility) Membership Functions

(ii) Sewer CDPM Model

Sewer CDPM model includes Sewermain blockage, Sewermain Backups, and Capacity issues

<u>Number of sewermain blockage / useful life</u>

Sewermain blockages restrict the flow of sewage in the system. Not only do they require attention from operations and maintenance staff, but they are also a liability issue because they can cause back-ups in the environment or to customer property. This performance measure factor identifies the sewermain history of blockages, both recently and over the life of the asset. Workshop participants indicated that the repeat occurrences would most of the time affect the same customers. The membership functions and their characteristics are shown in Figure 5-14. The data type to be used for this performance measure factor is the total number of sewermain blockages during the sewermain useful life ranging from 0 to 12 where 0 indicates the best customer performance zones and 8 or more indicates the worst customer performance zones.

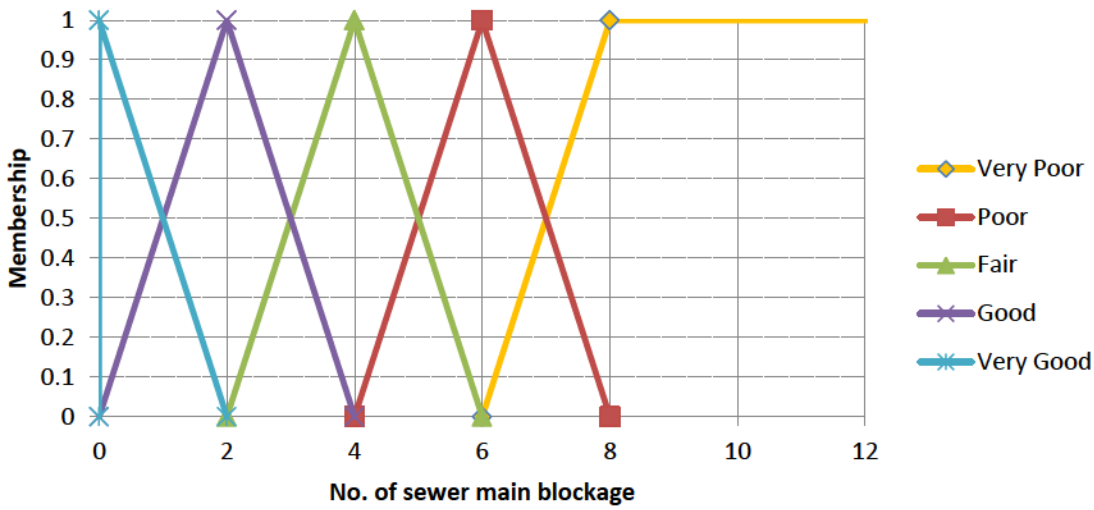


Figure 5-14 Sewermain Blockage Membership Functions

<u>Annual no. of sewermain backups/ segment</u>

During the workshop interview, the workshop participants came to a consensus that the customer understands a blocked sewer basement flooding. The customer also notices blocked sewers that cause flooding to the environment and produced odours. Therefore, it is recommended to measure the number of sewermain backups that may cause (basement floods, odour complaints due to blocked sewers, and /or floods to environment due to blocked sewers). The membership functions and their characteristics are shown in Figure 5-15. The data type to be used for this performance measure factor is the average annual sewermain backups per segment ranging from 0 to 5 where 0 indicates the best customer performance zones and 4 or more indicates the worst customer performance zones.

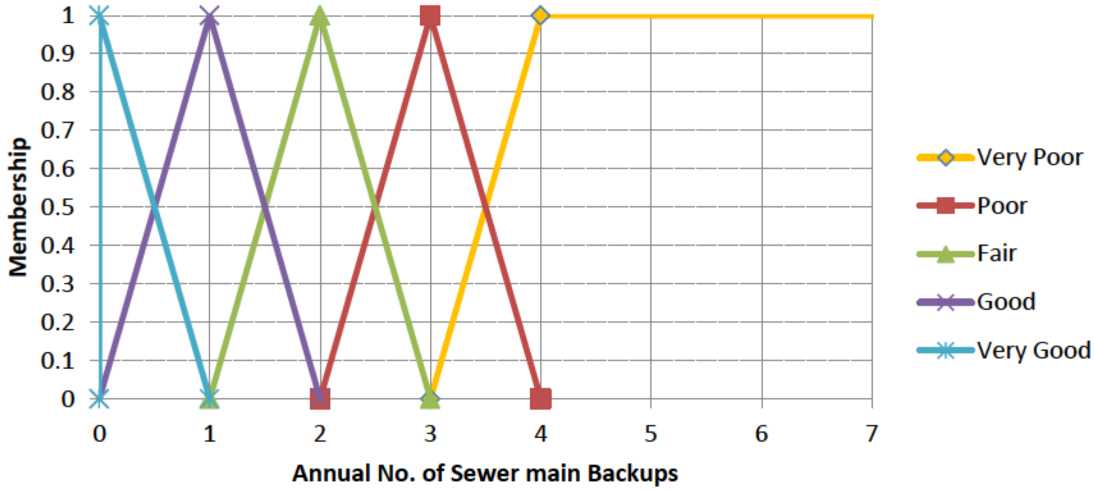


Figure 5-15 Sewermain Backups Membership Functions

<u>Capacity issues</u>

Customers experience capacity issues as overflows on their property. Hydraulic capacity is based on the peak value of depth of flow divided by the pipe diameter (d/D). The higher values indicate that the sewer is heavily utilized and, therefore, a greater concern for failure and a higher probability of reaching capacity. Replacement with a larger pipe should therefore be considered. Hydraulic Capacity data (d/D) is obtained from the City's sanitary model. The membership functions and their characteristics are shown in Figure 5-16. The data type to be used for this performance measure factor is peak value of depth of flow divided by the pipe diameter (d/D) ranging from 0.01 to 1 where 0.01 indicates the best customer performance zones and 0.85 or more indicates the worst customer performance zones.

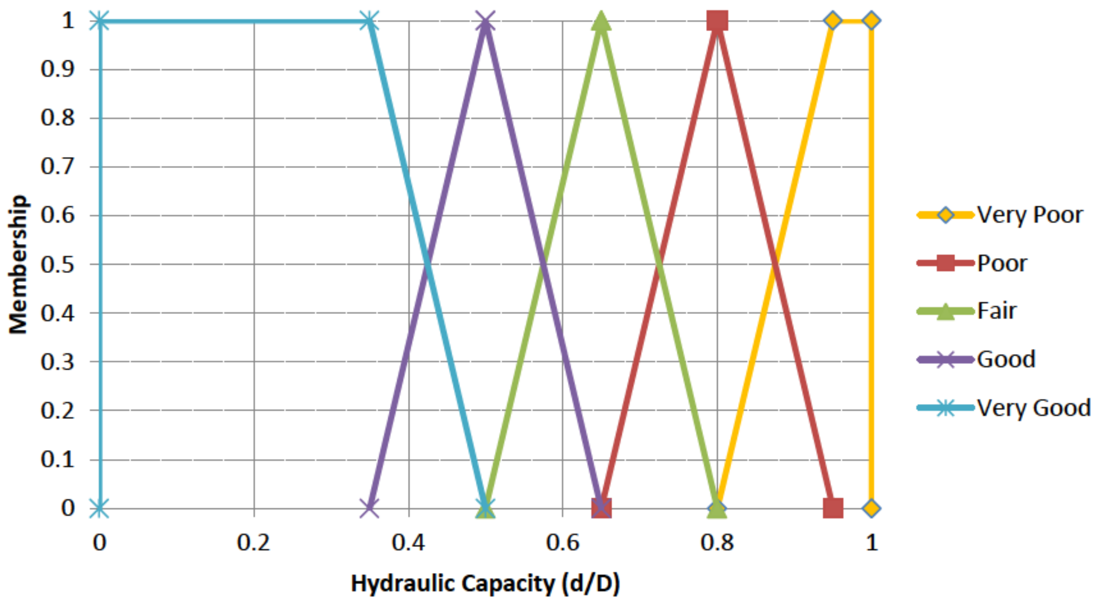


Figure 5-16 Hydraulic Capacity (d/D) Membership Functions

(iii) Roads CDPM Model

Road CDPM model includes road segment roughness; and annual number of crack seal/ segment

<u>Road Roughness</u>

Roughness is measured by Riding Comfort Index (RCI). The membership functions and their characteristics are shown in Figure 5-17. The RCI can vary in value from zero to ten. The data type to be used for this performance measure factor is RCI index ranging from 0 to 10 where 10 indicates the best customer performance zones and 2 or less indicates the worst customer performance zones.

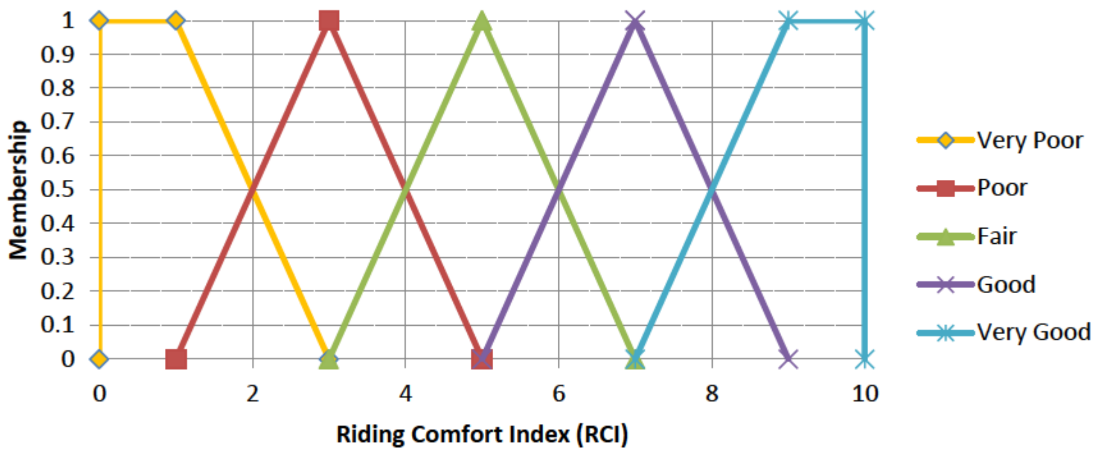


Figure 5-17 Riding Comfort Index (RCI) Membership Functions

<u>Annual number of crack seal/ segment</u>

The membership functions and their characteristics are shown in Figure 5-18. The data type to be used for this performance measure factor is annual number of crack seal/ segment ranging from 0 to 10 where 0 indicates the best customer performance zones and 8 or more indicates the worst customer performance zones.

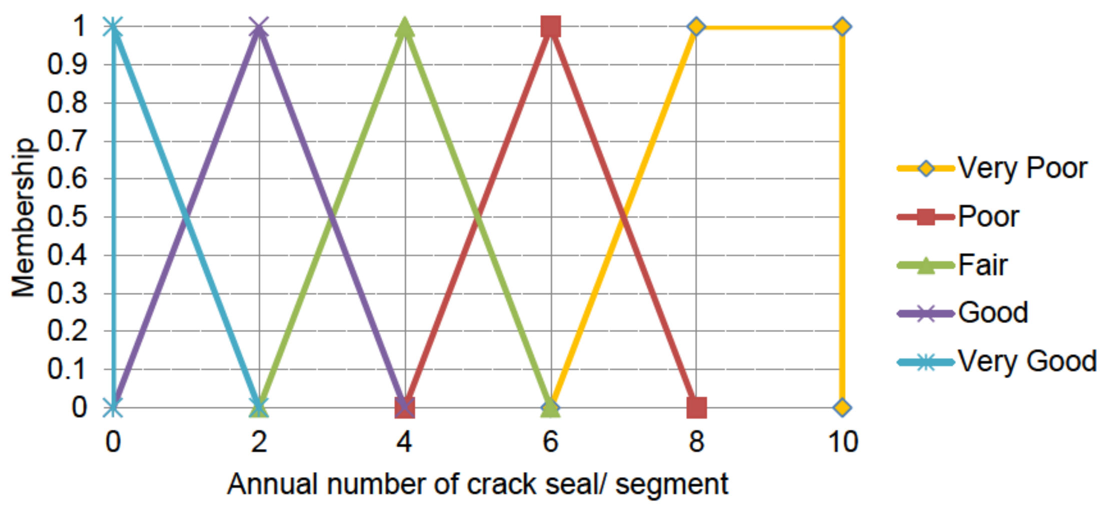


Figure 5-18 Annual Number of Crack Seal Membership Functions

5.2.4 CDPM Fuzzy Model Development

(i) Fuzzy Rule Base

Fuzzy “if-then” type rules are used to incorporate the expert’s knowledge and to establish the link between fuzzy input variables and output variables. The next step in the construction of the fuzzy performance model is to build the rule base between inputs and the output. Since we have four Models as follows: Road- includes 2 input factors, water- includes 4 input factors, sewer- includes 3 input factors, and overall- includes 3 input variables (one from each model). Each input is represented using five linguistic variables, 5^2= 25 rules for roads, 5^4= 625 rules for water, 5^3=125 rules for sewer, and 5^3= 125 rules for the overall model can be generated from these scenarios. An example of the traditional Fuzzy If-Then rules is:

IF # WQ complaints is “none” and # WP Complaints is “None” and # breaks is "None", and Accessibility is "good" THEN CDPM is “Very Good”.

A rule building methodology adopted from Shaheen (2005) and Fares (2008) is used, which use weighted average method to combine the factors’ performance depending on the weights. An example of the Fuzzy If-Then rules is shown Table 5-10 and Table 5-11.

Table 5-10 Number of Annual Water Quality Complaint If-Then Rules

Performance Measure		Impact On CDPM	
If # WQ complaints is	Very Low (None)	Then the CDPM index is	Very Good
If # WQ complaints is	Low [1 to 2/Km/ yr]	Then the CDPM index is	good
If # WQ complaints is	Average [3 to 5/Km/ yr]	Then the CDPM index is	Fair
If # WQ complaints is	high [5 to 10/Km/ yr]	Then the CDPM index is	Poor
If # WQ complaints is	Very High [>10/Km/ yr]	Then the CDPM index is	Very Poor

Table 5-11 Accessibility If-Then Rules

Performance Measure		Impact On CDPM	
If Accessibility (Duration of Interruption) is	Low	Then the CDPM index is	Very poor
If Accessibility (Duration of Interruption) is	Marginal	Then the CDPM index is	Fair
If Accessibility (Duration of Interruption) is	Good	Then the CDPM index is	Very Poor

Using the weights of factors, the combined performance impact of the different factors is calculated using the AHP method. The followings sections will summarize the steps followed in finding the equivalent impact of different combinations of all three Fuzzy models and the overall integrated level of the hierarchy.

(ii) Membership Function Aggregation

This involves translating input values to fuzzy set memberships. By defining values for the input variables, the membership value (μ) of each input variable is calculated applying the following Equation 5-5 for triangular distributions (Pedrycz and Gomide, 2007).

$$\mu\,(\mathrm{x}) = \begin{cases} 0 & if \quad x \leq a \; or \; x \geq b \\ \dfrac{x-a}{m-a} & if \quad x \in [a, m] \\ \dfrac{b-x}{b-m} & if \quad x \in [m, b] \end{cases}$$

Equation 5-5

Where (a) is the minimum, (m) is the most likely, (b) is the maximum, and (x) is the value at which the membership functions is required to be calculated after calculating the membership value for each input variable at different rules. The integrated membership function from each rule is then aggregated using the max operator. The maximum membership value of any performance measure membership function is used to truncate that performance measure membership function.

(iii) Defuzzification Process

Defuzzification is translating fuzzy output back to crisp system output. The final aggregated membership function is then defuzzified using one of the defuzzification methods. Some of the common defuzzification methods are (Yager and Zadeh, 1992):

1. <u>Center of gravity method</u>: the center of gravity method calculates the center of the distribution. (This is the method used in this study).
2. <u>Mean of Maximum</u>: The Mean of Maximum Method (MOM) is based on averaging the support values, which their membership values reach the maximum.

(iv) Factor Weighting

The AHP analysis was applied to water and sewer performance factors, where the top level of the hierarchy reflects the CDPM index for each model separately. Asset managers are required to prioritize factor in each level of the hierarchy using the pairwise comparison matrices. Performance factors are compared in pairs with respect to their importance in overall client driven performance measure index. The relative weights of the performance factors are then established as shown in Figure 5-7 below. On the other hand, road model had only two performance factors; therefore, asset managers were required to assign a relative weight to each of those factors directly.

Table 5-12 Performance Measure Factor Weights

Performance Measure	Factor Weight
Roads = 0.34	
Road Roughness Rating (RPI)	0.60
# Crack seal / segment	0.40
Water = 0.33	
# Water quality complaints	0.10
# Water pressure complaints	0.26
# Segment interruption (Breaks)	0.45
Average duration of interruption (Accessibility)	0.18
Sewer = 0.33	
Sewermains capacity issues	0.50
# Sewermains blockages	0.25
Annual number of sewermains backups / segment	0.25

5.2.5 CDPM Fuzzy Model Example and results

In order to demonstrate how CDPM fuzzy Logic model works, let us assume that we have two input variables [X1:#WQ complaints and X2: #WP complaints] for watermain segment and would like to calculate the CDPM index based on those two factors. Steps required to perform the fuzzy logic example are summarized as follows:

1. Define the membership functions for the input and the output variable, (*as discussed in Section 5.2.3 Fuzzy Membership Functions*). In this example, we are using (X1: # WQ complaints is 5 and X2: # WP complaints is 2) for a watermain segment. For example, the first rule shows the membership of (X1 is 5) therefore, X1 has a 50% membership poor and 50% membership to fair. Similarly for X2, it has 100% membership in fair as shown in Figure 5-19.

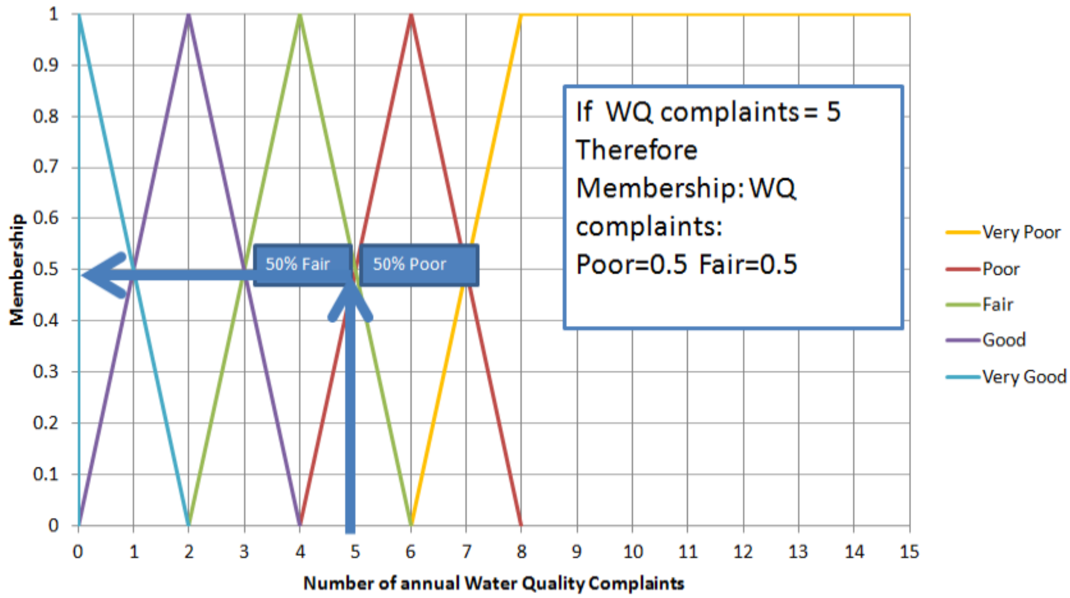


Figure 5-19 Sample WQ Membership Function

2. Expert's opinion was used to define the relationship between the inputs and the output variable in the form of (if-then) rules. (*As discussed in Section* (i) Fuzzy Rule Base) using the Table 5-13 and Table 5-14:

Table 5-13 Number of Annual Water Quality Complaints Rules

Performance Measure		Impact On CDPM	
If # WQ complaints is	Very Low (None)	Then the CDPM index is	Very Good
If # WQ complaints is	Low [1 to 2/Km/ yr]	Then the CDPM index is	good
If # WQ complaints is	Average [3 to **5**/Km/ yr]	Then the CDPM index is	**Fair**
If # WQ complaints is	high [**5** to 10/Km/ yr]	Then the CDPM index is	**Poor**
If # WQ complaints is	Very High [>10/Km/ yr]	Then the CDPM index is	Very Poor

Table 5-14 Number of Annual Water Pressure Complaints Rules

Performance Measure		Impact On CDPM	
If # WP complaints is	Very Low (None)	Then the CDPM index is	Very Good
If # WP complaints is	Low [1 to **2**/Km/ yr]	Then the CDPM index is	**Fair**
If # WP complaints is	Average or High [> 3/Km/year]	Then the CDPM index is	Very Poor

3. Calculated the membership value μ (X) for each input variable.

Firstly, the membership value of the X1 and X2 is calculated for each rule using Equation 5-5 and as shown in Figure 5-20.

Figure 5-20 CDPM Membership Values of the WQ& WP Input Variables

The implicated membership function from each rule is then aggregated using the max operator (*as discussed in Section* (ii) Membership Function Aggregation) as shown in Figure 5-21.

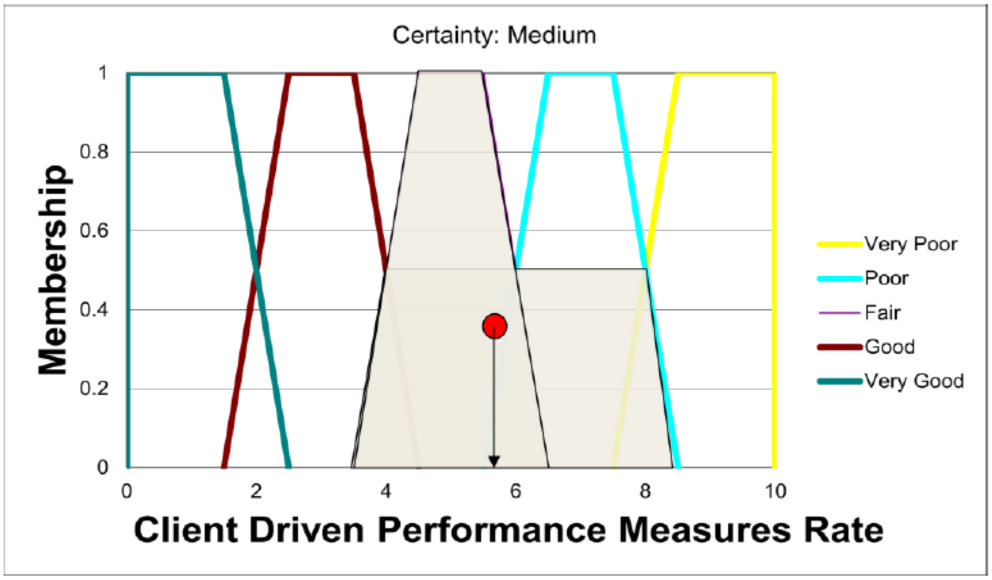


Figure 5-21 Aggregation of CDPM Membership Function

4. The final aggregated membership function is then defuzzified. (*As discussed in Section* (iii) Defuzzification Process). Therefore, the CDPM index can be calculated using Equation 5-6.

$$CDPM\ Index = \frac{\sum_{i=1}^{N}(W(Xi)\ .C(Xi).\mu(Xi))}{\sum_{i=1}^{N} W(Xi).\mu(Xi)}$$

Equation 5-6

Where

Xi: input variable (e.g. number of breaks, number of complaints, etc.)

W(Xi): Weight of input variable (Xi), range 0-1

C(Xi): Center of CDPM index range for input variable (Xi), range 0-10

µ(Xi): is the membership value for input variable (Xi), range 0-1

N: total number of input variables

By applying Equation 5-6 to the examples above, where N is number of variables (here: 2) , therefore

CDPM Index = $\frac{0.33(5 * 0.5 + 7*0.5) + 0.67(5*1)}{0.33(0.5+0.5) + 0.67(1)}$ = **5.33**

Table 5-15 shows the overview of CDPM calculation process. The input values for CDPM variables are shown in column (A). Using the fuzzy membership values and fuzzy logic rules, then the expected CDPM for each input variable is calculated as shown in column (B). Similarly, the minimum and maximum CDPM for each variable can be computed and are shown in Columns C & D. The weighting of each variable is assigned using Delphi and/or AHP approach (i.e. column E). Then the Aggregate CDPM index can be established by multiplying the CDPM index of each variable by its weight (i.e. column F, G & H). Finally, the sum of the aggregate CDPM index will provide the Overall CDPM index.

Table 5-15 Summary of CDPM Index Results

INPUT DATA		Results						
Pipe ID	W01	CPDM Index (Xi)			Weight	Aggregate CDPM		
	A	B	C	D	E	F=BxE	G=CxE	H=DxE
Variable	Value	Expected	Min	Max	W(Xi)	Expected	Min	Max
# Water quality complaints	5	6	3.5	8.5	0.33	1.98	1.16	2.8
# Water Pressure complaints	2	5	3.5	6.5	0.67	3.35	2.34	4.35
					Overall Performance Rating Sum (F, G, H)	5.33	3.5	7.16

Similarly, the approach described above can be applied to both sewer and road models to get an overall CDPM index for the integrated segment.

5.3 Optimization Model Development

Optimization is utilized to produce a final optimized decision-making framework for each lifecycle option of the integrated Corridor rehabilitation, through the integration of the risk management scoring, condition assessment, performance management, and economic loss of remaining service life. While there are several optimization options available, optimized decision-making is computationally intensive requiring a lot of calculations. The selected integer-programming approach is influenced by the availability of software capable of supporting this type of analysis and data required to drive it.

All optimization problems have several elements in common. They all have (1) decision variable, the variable that decision makers can choose, either directly or indirectly, which affect the value of the objective function. (2) Objective function, whose value is to be optimized (minimize or maximize). (3) Constraints, a set of constraints that allow the unknowns to take on certain values but exclude others. In searching for the values of the decision variables that optimize the objective function, we must choose values that satisfy the constraints.

5.3.1 Problem Statement

Work progress in a Road, Watermain, or Sewermain replacement/ rehabilitation projects can be coordinated by providing a better decision making framework to answer the following questions: What are the intervention (replace, rehabilitate, etc.) actions required and when is the best time to do them? For a short and long term, planning horizon that would optimize the allocation of budget by maximizing risk reduction for minimum cost subject to condition, performance, and budget constraints. This problem is tackled by adopting a multi-stage integer-programming algorithm where multi-year plans are optimized on a year-by-year basis. A typical plan establishes, for a given year and for each asset (R/W/S), the most appropriate and cost-effective renewal action (if any). Figure 5-22 shows the flowchart of the initial screening process required to propose projects to the network level optimization program.

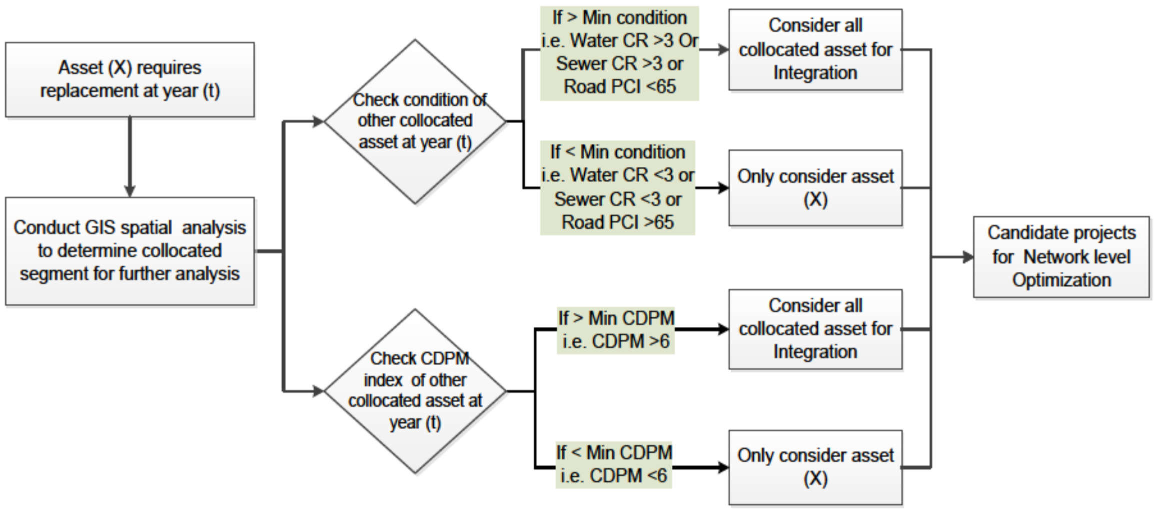


Figure 5-22 Initial Screening for Optimization Process

After conducting the initial screening, assets are assessed for risk and performance; the following steps summarize the decision making approach as shown in Figure 5-23:

- Calculate the integrated overall risk index, and identify risk index trigger levels for a Major, Moderate, and Minor risk
- Define action option for each project (e.g. repair, rehabilitate, replace, or change operation and maintenance procedure, etc.)
- Assess residual risk for each alternative / option
- Then, calculate risk reduction per dollar spent and rank projects accordingly

- Apply all constraints such as funding level, minimum acceptable Level of service, performance, condition, etc.
- Conduct optimization via integer programming
- Check that assets at major risk are included in the recommended intervention list
- If any high and major risk assets were not included in the recommended project list. Either explore other alternatives, possibly shorter-term solutions to manage this risk at less cost or add the major risk index as a constraint
- Re-assess the cost/risk reduction and conduct optimization
- Summarize recommended investment /projects

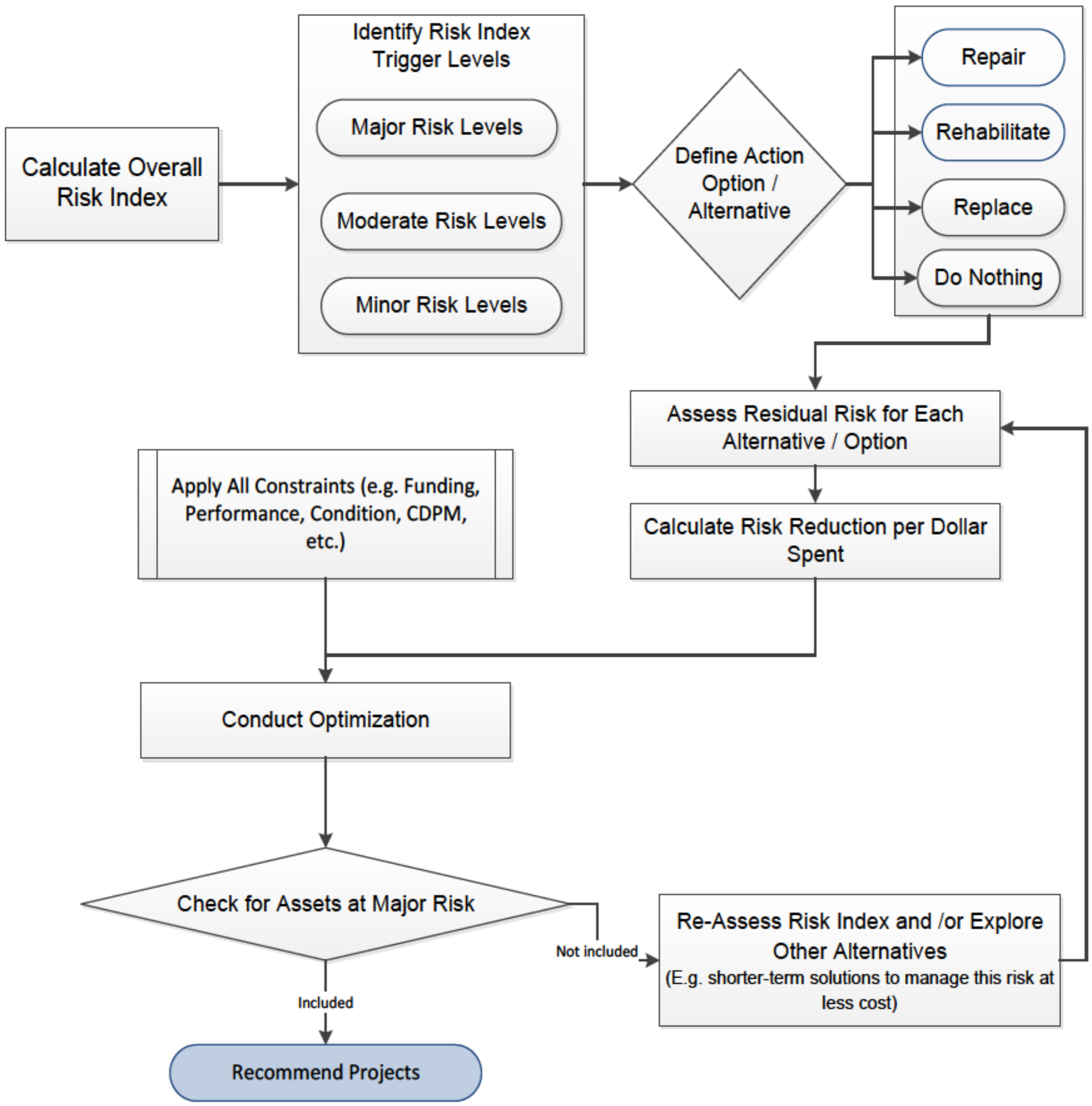


Figure 5-23 Decision Making Approach

5.3.2 Decision Variables

On any infrastructure project (road, sewer or water segment) planned for replacement within a given time period (t), several identified Scenario /alternative (Si) for replacement strategies are considered for analysis. Each type of strategy has Si Scenario /alternatives (i=1,…, i). For example, there might be S1- Road

Full Construction, S2-Sewer Full Construction, S3-Water Full Construction, S4-Water/ Road Construction, S5-Sewer/Road Construction, S6-Water/Sewer/Road Construction, and S7-Water/Sewer (trenchless) strategies available for selection. Therefore, the decision variables include:

- The total number of projects and cost ;
- The planned replacement year of each project t (t=1,2,…t years);
- The index of the selected Scenario /alternative (e.g. S1- Road Full Construction, S2-Sewer Full Construction, S3-Water Full Construction, etc.)

5.3.3 Objective Function Formulation

The objective function of this multi-stage integer-programming model is defined to maximize risk reduction for minimum cost discounted to the present value over the time frame while taking all the quantifiable costs and benefits terms into account. The process includes quantifying the risk, identifying mitigation measures and then setting out to reduce the risks in the most cost effective manner. The approach to address risk is covered in the Section 5.1 Integrated Risk Model Development. The discounted cash flow pattern in each time period is defined based on the government bond issued.

Suppose *Z* is the net risk reduced per cost spent and is described by:

$$Max\ Z = \sum_{j=1}^{m} Z_j$$

Equation 5-7

$$\boldsymbol{Z_j} = \sum_{i=1}^{7} \frac{\Delta Risk_{ij}}{\text{Scenario NPV}_{ij}}$$

Equation 5-8

Such that:

Z $_j$: the risk reduced per dollar spent for an Asset j

J: asset under consideration (i.e. road segment, water segment, or sewer segment)

m: the total number of assets under consideration in the network/ sub network

Δ Risk $_i$: risk reduction for identified Scenario /alternative. Each Risk reduction includes:

$$\boldsymbol{\Delta Risk_i} = \ (COF_i \, . \, POF_{B_{it}}. \, SC_i - \, COF_i \, . \, POF_{A_{it}}. \, SC_i). I_{ijt}$$

Equation 5-9

Where

i : Number of identified Scenario /alternative (i.e. S1- Road Full Construction , S2-Sewer Full Construction, S3-Water Full Construction, S4- Water/ Road Construction, S5-Sewer/Road Construction, S6-Water/Sewer/Road Construction, and S7-Water/Sewer (trenchless))

COF $_i$: Consequence of failure index (Range 1 to 5)

POF $_{B\,it}$: Probability of failure before Intervention (Range 0 to 1) at Time t

POF $_{A\,it}$: Probability of failure after Intervention (Range 0 to 1) at Time t

SC $_i$: The NPV of Asset capital construction cost (replacement) for identified Scenario /alternative ($)

I_{ijt} : Binary variable that determines which type of asset intervention should be applied in time period t (where t = 1 to 20 years, analysis period)

Scenario NPV $_{ij}$ = net cost spent discounted to the present value over the analysis time frame while taking all the quantifiable costs and benefits terms into account for an asset j. Each scenario cost includes:

Scenario NPV $_{ij}$ = C1 + C2 – B1

Equation 5-10

Where

C1: The Asset operation and maintenance cost (e.g. crack/ seal for roads, pipe break for water, spot repair for sewer);

C1 = $(OM_{ij}\ .L_{ij}).\left[\frac{(1+r)^{t}-1}{r(1+r)^{t}}\right]$

Equation 5-11

Where,

OMj*:* is the operation and maintenance cost for asset j per year (estimated by asset class based on type of asset)

Lj*: is the asset segment length*

t: is the analysis period (Years)

r: is the interest rate

C2 = $(FC_{ij} + VC_{ij}\ .\ DP_{ij}.L_{ij.} + RRC_{ij}.L_{ij}).(1+ r)^{-t}$

Equation 5-12

Where,

FC*ij* = coefficients derived from a linear regression of the cost of Construction based on several existing design capacities and represent the Fixed charges of the total construction cost ($) or estimated from municipalities based on previous history.

$\boldsymbol{VC_{ij}}$: Variable cost coefficients dependent on the proposed design parameters (DP) ($)

$\mathbf{RRC_{ij}}$: Road Restoration Costs encountered by the city to restore a road to its original state. It should be noted that this RRC equals to zero for "road reconstruction only" alternatives as it is normally included in the fixed and variable cost.

$\boldsymbol{DP_{ij}}$: the design parameter (Diameter range for water / sewermains, Road width and class for roads) for the new asset.

$\mathbf{L_{ij}}$: the asset /segment length

$\boldsymbol{I_{it}}$: Binary variable that determines which type of asset intervention should be applied in time period t (where t = 1 to 20 years, analysis period)

tj: the analysis period (Years) for asset j

r : interest rate

B1 = Residual value

$$\mathbf{B1} = (n - A_{jt})/n.\ (FC_{ij} + VC_{ij}\ .\ DP_{ij}.L_{ij} + RRC_{ij}.L_{ij}).(1+r)^{-t}$$

Equation 5-13

$\boldsymbol{n_j}$: estimated useful life for asset j

$\mathbf{A_{jt}}$: estimated Age for asset j at the analysis year t

$(\boldsymbol{FC_{ij}} + \boldsymbol{VC_{ij}}\ .\ \boldsymbol{DP_{ij}}.\mathbf{L_{ij}} + \mathbf{RRC_{ij}}.\mathbf{L_{ij}})$*: is the* replacement cost of the asset j

5.3.4 Constraint Set

1. **Budget Limitation constraint**:

Municipalities have separate budget for water, sewer and road departments. The water and sewer budget is rate based while the road budget is tax based. Therefore it is important to consider them separately.

$$\sum Replacement\ Cost_{Road}\ .I_{ijt} \leq\ \ Annual\ Budget_{Road}\ \ at\ year\ t$$

Equation 5-14

$$\sum Replacement\ Cost_{water}\ \ .I_{ijt} \leq\ \ Annual\ Budget_{water}\ \ at\ year\ t$$

Equation 5-15

$$\sum Replacement\ Cost_{sewer}\ \ .I_{ijt} \leq\ \ Annual\ Budget_{sewer}\ \ at\ year\ t$$

Equation 5-16

$$\sum_{i=1}^{7} I_{ijt}\ \leq 1 \quad \forall i,j,t$$

$I_{ijt}\ \in \{0,1\}$ Binary constraint, this constraint ensures that one scenario / alternative can only be initialized once exclusively along the timeline. However, it is not necessary for them to be initialized if it is not cost effective in the optimization process.

Where ,

$$\boldsymbol{Replacement\ Cost_{Road\ (j)}} = \left(FC_{1j} + VC_{1j}.DP_{1j}.L_{1j}\right).I_{1t} + (FC_{4j} + VC_{4j}.DP_{4j}.L_{4j} + CS_R.RRC_{4j}.L_{4j}).I_{4t} + (FC_{5j} + VC_{5j}.DP_{5j}.L_{5j} + CS_R.RRC_{5j}.L_{5j}).I_{5t} + (FC_{6j} + VC_{6j}.DP_{6j}.L_{6j} + CS_R.RRC_{6j}.L_{6j}).I_{6t}$$

Equation 5-17

CS$_R$: *is the* Cost-Sharing percentage covered from roads department budget to recover the road restoration costs (%).Typically, it is negotiated between the road, water, and sewer department based on the motive for excavation.

$$\boldsymbol{Replacement\ Cost_{Water\ (j)}} = \left(FC_{3j} + VC_{3j}.DP_{3j}.L_{3j} + RRC_{3j}.L_{3j}\right).I_{3t} + (FC_{4j} + VC_{4j}.DP_{4j}.L_{4j} + CS_W.RRC_{4j}.L_{4j}).I_{4t} + (FC_{6j} + VC_{6j}.DP_{6j}.L_{6j} + CS_W.RRC_{6j}.L_{6j}).I_{6t}$$

Equation 5-18

CS_W: *is the* Cost-Sharing percentage covered from Water department budget to recover the road restoration costs (%).

$$\boldsymbol{Replacement\ Cost_{Sewer\ (j)}} = \left(FC_{2j} + VC_{2j}.DP_{2j}.L_{2j} + RRC_{2j}.L_{2j}\right).I_{2t} + (FC_{5j} + VC_{5j}.DP_{5j}.L_{5j} + CS_S.RRC_{5j}.L_{5j}).I_{5t} + (FC_{6j} + VC_{6j}.DP_{6j}.L_{6j} + CS_S.RRC_{6j}.L_{6j}).I_{6t}$$

Equation 5-19

CS_S: *is the* Cost-Sharing percentage covered from Sewer department budget to recover the road restoration costs (%).

2. **Performance Limitation Constraint**:

Performance constraint is introduced to ensure that the overall network performance will be improved after selecting any asset intervention scenario. For example, the optimization process will elect to recommend intervention for the asset having poor performance first to improve the overall network performance. Therefore the overall network performance after interventions should be the best of all possible performance levels for any combination of possible interventions.

$$Average\ Network(CDPM_j\,.\,\mathrm{I_{ijt}}) \geq \mathrm{CDPM}_{Min}$$

Equation 5-20

$$Average\ Network\left(CDPM_j\,.\,\mathrm{I_{ijt}}\right) \leq \mathrm{CDPM}_{Max}$$

Equation 5-21

$$Average\ Network(CDPM_j\,.\,\mathrm{I_{ijt}}) = \frac{1}{m}\left(\sum_{j=1}^{m} CDPM_j - \sum_{i=1}^{7}\sum_{j=1}^{m} CDPM_{ij}\,.\,\mathrm{I_{ijt}} + CDPM_{new}.\sum_{i=1}^{7}\sum_{j=1}^{m} \mathrm{I_{ijt}}\right)$$

Equation 5-22

Where,

m: is the total number of network assets.

CDPM $_{new}$: represents the CDPM index when a new asset is installed. (CDPM $_{new}$ assumed to equal 1.0)

CDPM: represents the client driven performance measure index (refer to Section 5.2 for calculation). For example CDPM $_{min}$ can equal to 1 and CDPM $_{max}$ is 10).

3. **Condition Limitation Constraint**:

Condition constraint is introduced to ensure that the overall network condition or the Remaining Service life (RSL) of the network is increased after selecting any asset intervention scenario. For example, the optimization process will elect to recommend intervention for the asset having poor condition first to improve the overall network condition. Therefore the overall network condition after interventions should be the best of all possible condition rating for any combination of possible interventions.

$$Average\ Network(Condition_i\,.\,\mathrm{I_{it}}) \geq \ \mathrm{Condition}_{Min}$$

Equation 5-23

$$Average\ Network(Condition_i\,.\,\mathrm{I_{it}}) \leq \ \mathrm{Condition}_{Max}$$

Equation 5-24

$$Average\ Network(Condition_j\,.\,\mathrm{I_{ijt}}) = \frac{1}{m}\left(\sum_{j=1}^{m} CR_j \ - \sum_{i=1}^{7}\sum_{j=1}^{m} CR_{ij}\,.\,\mathrm{I_{ijt}} \ + CR_{new}.\sum_{i=1}^{7}\sum_{j=1}^{m}\mathrm{I_{ijt}}\right)$$

Equation 5-25

Where,

m: is the total number of network assets.

CR_{new}: represents the condition rating index when a new asset is installed; this index equal: CR_{new_road} is 100, CR_{new_water} is 1, and CR_{new_sewer} is 1

CR: represents the condition rating index. A minimum acceptable condition is defined for each asset class. Any Asset segment will become a candidate for a maintenance or rehabilitation treatment only when its condition falls below the minimum acceptable condition. For example for watermains $Condition_{min}$ is 3 and $Condition_{max}$ is 5.

5.3.5 Optimization

Any Investment planning problems involve various Yes - No decisions, which can be considered as the 0−1 values of integer variables. Consider an investment model with 100 changing cells all constrained to binary. Because there are only two values for each binary value, 0 and 1 there are potentially 2^{100} feasible solutions.

For example, for an identified project that has three 0−1 alternatives S= (S1, S2, S3), the only vectors that could be solution vectors are (0, 0, 0), (0, 0, 1), (0,1, 0), (0,1,1), (1,0,0), (1,0,1), (1,1,0), (1, 1, 1). Therefore, by checking each of these 2^3 = 8 vectors we can identify the set of all feasible solutions, and the set of optimum solutions for the problem. The above optimization problem, identifies seven alternatives for each project (S1- Road Full Construction, S2-Sewer Full Construction, S3-Water Full Construction, S4- Water/ Road Construction, S5-Sewer/Road Construction, S6-Water/Sewer/Road Construction, and S7-Water/Sewer (trenchless)) therefore by checking each of these $2^7 = 128$ vectors we can identify the set of all feasible solutions, and also the set of optimum solutions for this problem. Additionally, over 100 projects per year need to be examined.

The method of Complete Enumeration of all possible solutions is usually impractical. Therefore using a more practical approach such as *Branch and Bound* method is more appropriate. Branch and bound is an approach to search for an optimum feasible solution by doing only a partial enumeration. The Branching means that the algorism systematically searches through the set of all feasible binary solutions, creating branches, of solutions as it goes. The Bounding part of the approach computes and uses both upper and lower bounds for the optimum objective value.

In this research, Excel Solver was used to perform the Branch and Bound approach for the above integer-programming problem. Among the limitation of using Excel Solver is the inadequate number of changing cells, i.e. Excel Solver limits the number of changing cells to 190 cells. Since each project has, seven (7) alternatives/ scenarios to be evaluated therefore only twenty seven (27) projects can be evaluated at one time(i.e. 190/7=27.14).

5.3.6 Summary of Optimization model

Objective function:

$$Max\ Z = \sum_{j=1}^{m} Z_j$$

Such that:

$$Z_j = \sum_{i=1}^{7} \frac{\Delta Risk_{ij}}{\text{Scenario NPV}_{ij}}$$

$$\Delta Risk_i = (COF_i \,.\, POF_{B_{it}} . \, SC_i - COF_i \,.\, POF_{A_{it}} . \, SC_i). I_{ijt}$$

Scenario NPV $_{ij}$ = C1 + C2 – B1

$$\text{C1} = (OM_{ij}\ .L_{ij}).\left[\frac{(1+r)^t - 1}{r(1+r)^t}\right]$$

$$C2 = (FC_{ij} + VC_{ij}\ .\ DP_{ij}.L_{ij.} + \text{RRC}_{ij}.\text{L}_{ij}).(1+ r)^{-t}$$

$$\text{B1} = (\text{n} - \text{A}_{jt})/\text{n}.\ (FC_{ij} + VC_{ij}\ .\ DP_{ij}.L_{ij} + \text{RRC}_{ij}.\text{L}_{ij}).(1+ r)^{-t}$$

Subject to

Budget Limitation constraint

$$\sum Replacement\ Cost_{Road}\ .I_{ijt} \leq\ Annual\ Budget_{Road}\ \ at\ year\ t$$

$$\sum Replacement\ Cost_{water}\ .I_{ijt} \leq\ Annual\ Budget_{water}\ \ at\ year\ t$$

$$\sum Replacement\ Cost_{sewer}\ .I_{ijt} \leq\ Annual\ Budget_{sewer}\ \ at\ year\ t$$

$$\sum_{i=1}^{7} I_{ijt} \leq 1 \quad \forall i,j,t$$

$I_{ijt} \in \{0,1\}$ Binary constraint,

Such that:

$$\boldsymbol{Replacement\ Cost_{Road\ (j)}} = \left(FC_{1j} + VC_{1j}.DP_{1j}.L_{1j}\right).I_{1t} + (FC_{4j} + VC_{4j}.DP_{4j}.L_{4j} + CS_R.RRC_{4j}.L_{4j}).I_{4t} + (FC_{5j} + VC_{5j}.DP_{5j}.L_{5j} + CS_R.RRC_{5j}.L_{5j}).I_{5t} + (FC_{6j} + VC_{6j}.DP_{6j}.L_{6j} + CS_R.RRC_{6j}.L_{6j}).I_{6t}$$

$$\boldsymbol{Replacement\ Cost_{Water\ (j)}} = \left(FC_{3j} + VC_{3j}.DP_{3j}.L_{3j} + RRC_{3j}.L_{3j}\right).I_{3t} + (FC_{4j} + VC_{4j}.DP_{4j}.L_{4j} + CS_W.RRC_{4j}.L_{4j}).I_{4t} + (FC_{6j} + VC_{6j}.DP_{6j}.L_{6j} + CS_W.RRC_{6j}.L_{6j}).I_{6t}$$

$$\boldsymbol{Replacement\ Cost_{Sewer\ (j)}} = \left(FC_{2j} + VC_{2j}.DP_{2j}.L_{2j} + RRC_{2j}.L_{2j}\right).I_{2t} + (FC_{5j} + VC_{5j}.DP_{5j}.L_{5j} + CS_S.RRC_{5j}.L_{5j}).I_{5t} + (FC_{6j} + VC_{6j}.DP_{6j}.L_{6j} + CS_S.RRC_{6j}.L_{6j}).I_{6t}$$

Performance Limitation constraint

$$Average\ Network(CDPM_j\,.\mathrm{I_{ijt}}) \geq \mathrm{CDPM}_{\boldsymbol{Min}}$$

$$Average\ Network\left(CDPM_j\,.\mathrm{I_{ijt}}\right) \leq \mathrm{CDPM}_{\boldsymbol{Max}}$$

Such that,

$$Average\ Network(CDPM_j\,.\mathrm{I_{ijt}}) = \frac{1}{m}\left(\sum_{j=1}^{m} CDPM_j - \sum_{i=1}^{7}\sum_{j=1}^{m} CDPM_{ij}\,.\mathrm{I_{ijt}} + CDPM_{new}.\sum_{i=1}^{7}\sum_{j=1}^{m}\mathrm{I_{ijt}}\right)$$

Condition Limitation constraint

$$Average\ Network(Condition_j\,.\mathrm{I_{ijt}}) \geq \mathrm{Condition}_{\boldsymbol{Min}}$$

$$Average\ Network(Condition_j\,.\mathrm{I_{ijt}}) \leq \mathrm{Condition}_{\boldsymbol{Max}}$$

Such that,

$$Average\ Network(Condition_j\,.\mathrm{I_{ijt}}) = \frac{1}{m}\left(\sum_{j=1}^{m} CR_j - \sum_{i=1}^{7}\sum_{j=1}^{m} CR_{ij}\,.\mathrm{I_{ijt}} + CR_{new}.\sum_{i=1}^{7}\sum_{j=1}^{m}\mathrm{I_{ijt}}\right)$$

Where,

Z_j : Risk reduced per dollar spent for an Asset j

j : Asset under consternation

m: Total number of assets under consideration in the network/ sub network

Δ Risk $_i$: Risk reduction for identified Scenario /alternative.

i : Number of identified Scenario /alternative

COF $_i$ = Consequence of failure index

$POF_{B\,it}$: Probability of failure before Intervention at Time t

$POF_{A\,it}$: Probability of failure after Intervention at Time t

SC $_i$: NPV of Asset capital construction cost (replacement) for identified Scenario /alternative ($)

I_{ijt} : Binary variable that determines which type of asset intervention should be applied in time period t

Scenario NPV $_{ij}$: net cost spent discounted to the present value over the analysis time frame for an asset j.

OMj : the operation and maintenance cost for asset j per year

Lj *: the asset segment length*

t: *the analysis period (Years)*

r: *the interest rate*

FC_{ij} : Fixed charges of the total construction cost ($)

VC_{ij} : Variable cost coefficients ($)

RRC_{ij} : Road Restoration Costs to restore road to it is original state.

DP_{ij} : Design parameter (Diameter range for water / sewermains, Road width and class for roads) for the new asset.

t j: the analysis period (Years) for asset j

n_j : estimated useful life for asset j

A_{jt} : estimated Age for asset j at the analysis year t

CS_R: Cost-Sharing percentage covered from roads department budget to recover the road restoration costs (%).

CS_S: Cost-Sharing percentage covered from Sewer department budget to recover the road restoration costs (%).

CS_W: Cost-Sharing percentage covered from Water department budget to recover the road restoration costs (%).

CDPM: Represents the client driven performance measure index

$CDPM_{new}$: Represents the CDPM index when a new asset is installed.

CR: Represents the condition rating index.

CR_{new}: Represents the condition rating index when a new asset is installed

5.4 Prototype Tool Development

In order to make it easy for decision makers to use and implement the developed Models, it is automated by converting the developed methodology into a user-friendly prototype tool. This tool is developed using the visual basic applications (VBA) programming language and macros. The VBA allows programmers to develop user-defined functions that can be run through different Microsoft Office Applications (Ms - Access and Ms - Excel), and ESRI ArcGIS software. The integrated prototype application is implemented as a set of tool set modules; each module addresses one stage of the integrated planning process as shown in Figure 3-2. The prototype tools in this research are developed using the research methodology presented in Chapter 3.

5.4.1 Prototype Tool Development Overview

The asset management decision-making process discussed earlier will be implemented in this section in the context of tool development. This tool was developed to automate the process; Figure 3-8 shows the system architecture for the development process. The application development process shown is composed of three main modules that serve on all interfaces of the tool; each module contains some processes. As indicated in this figure, there are some mutual relations between the modules which illustrate how they are linked together. This Integrated Decision Support System (IDSS) has three modules that enable analytics driven cross organization planning as discussed in Table 5-16.

Table 5-16 Integrated Decision Support System (IDSS) Overview

	Central Asset Register (Database Design)	Integrated Decision Support System (IDSS) Modules		
		Integrated Risk Assessment - IRA module	**Performance Assessment – CDPM Module**	**Investment Planning – ODM module**
Overview	• Prepare data in a structured format to enable further analysis of Asset • Merge discrete inventories into one central Access database	• Established probability & consequence of failure profile. • Predict future risk events • Expected asset service life • Evaluate historical record & forecast risk events and their environmental, operation, social & economic impact.	• Analyze performance & assign CDPM index • Calculate integrated Performance index using predictive and historical values.	• Optimize investment to maximizing risk reduction for minimum cost • Identify projects across department for future capital investment using optimization techniques
Groundwork (starting point)	• Conduct spatial analysis. Collect data for key attributes (physical, condition, O&M, etc.)	• Apply AHP weighting • QA/QC data	• Collect & apply Fuzzy logic parameters	• Collect all financial information • Utilize output from IRA & CDPM modules
Analysis	• Merge discrete inventories into one central MS-Access database.	• Predict future probability of failure & remaining useful life • Integrate & Cluster CoF indices	• Link key performance measure to customer expectation • Integrate level of service improvement analysis.	• Conduct optimization
Key output	• central database • Multi-layer querying	• Probability of failure score • Consequence of failure index	• CDPM index • Deterioration profile	• List of projects with the optimal intervention plan • Year of intervention • Funding requirement

5.4.2 Data Preparation

Data input by the user(s) and data converted or calculated by the model will be stored in one central Microsoft Access database module. The model can reuse the stored data during the reporting process. The first step is to prepare the data into the required format for further analysis.

The IDSS utilizes a common Hierarchy and Registry design capturing all assets managed by Asset Class (i.e. Water, Sewer, and Road). It is based on a Centralized “data warehouse” replacing current various data sources throughout each of these asset classes. Data tables can be combined into a central database or stored and managed remotely and integrated / linked. Information is stored in its base format and combined as needed to support business functions and reporting. The following list summarizes these major Asset registers:

- Inventory record
- Condition record
- Maintenance record
- Risk management record
- Performance indicators records
- Capital & operating budget
- Projected investment plan

Figure 5-24 shows a sample of the data warehouse design and the attribute list for the developed IDSS model.

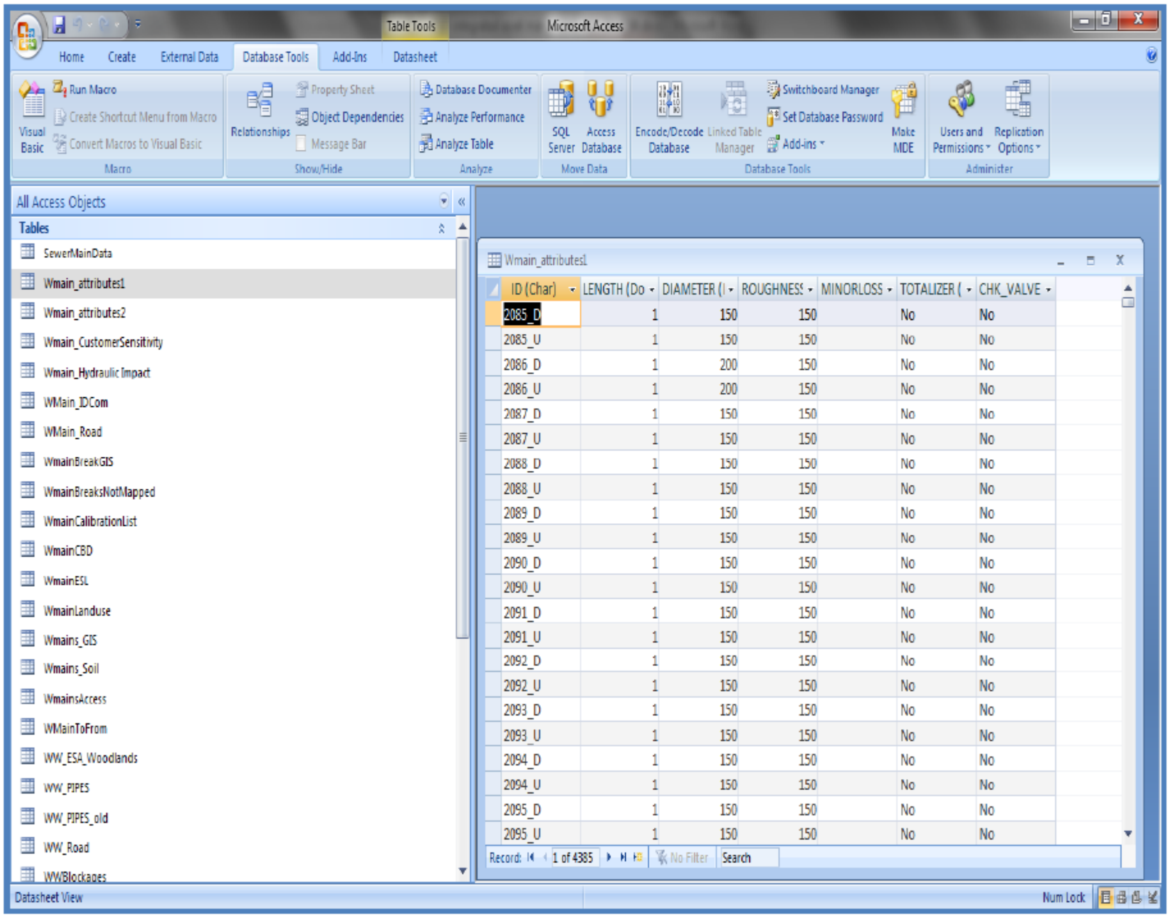


Figure 5-24 Sample Data Warehouse Database Tables for Watermains

5.4.3 Integrated Risk Assessment - IRA Module

The risk assessment module is divided into Consequence of failure and likelihood of failure as shown in Figure 5-25. Additionally Figure 5-26 shows the overall IRA module process and data flow framework. The consequence of a failure module is divided into four main parameters (Economic, Operational, Social, and Environmental). Each parameter is evaluated and ranked based on a number of criteria. The criteria were discussed in Section 5.1 Integrated Risk Model Development, and a scoring system and range was developed to ensure that the Integrated Risk Assessment (IRA) value calculated will identify road segment, watermains and sewermains at a higher risk of failure. Section 5.1

Integrated Risk Model Development identifies the parameters, criteria, score ranges, and weighting factors used to develop IRAs for linear water assets. These criteria are then entered into the risk assessment asset register as tables. Subsequently, a set of queries are conducted to assign these score to each asset using SQL script.

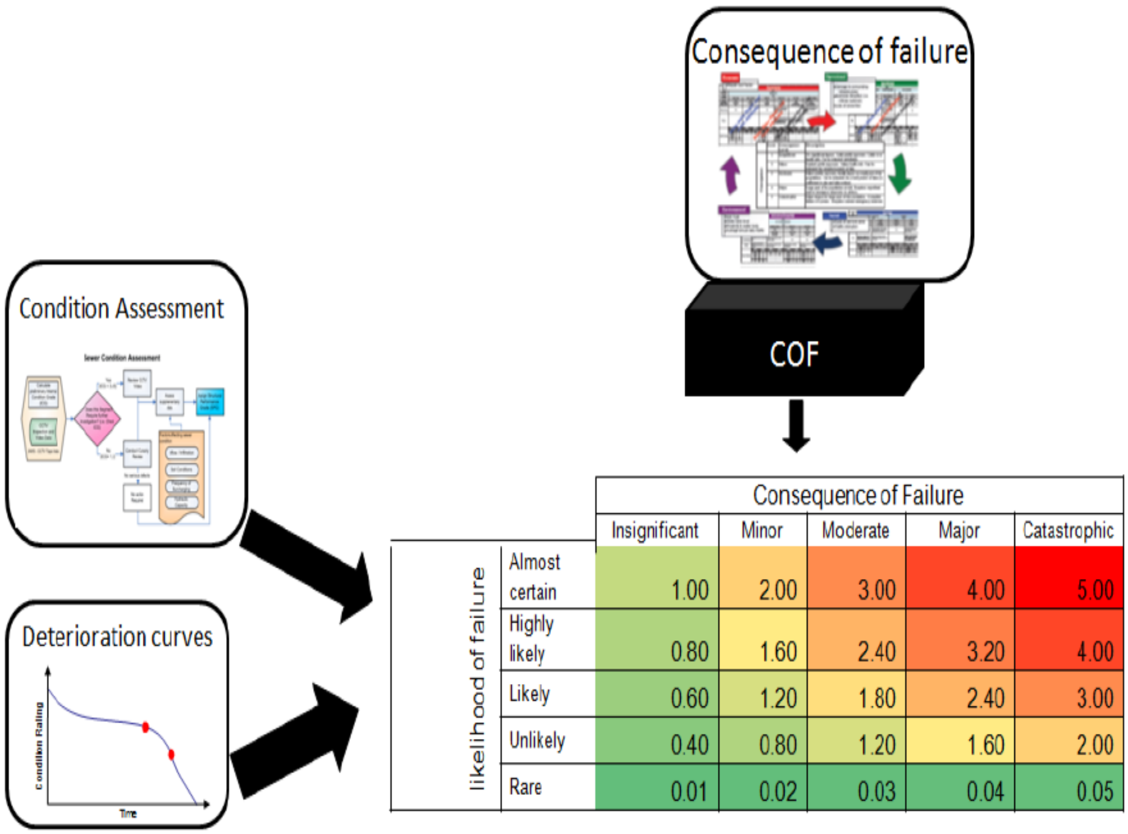


Figure 5-25 Integrated Risk Assessment - IRA Module

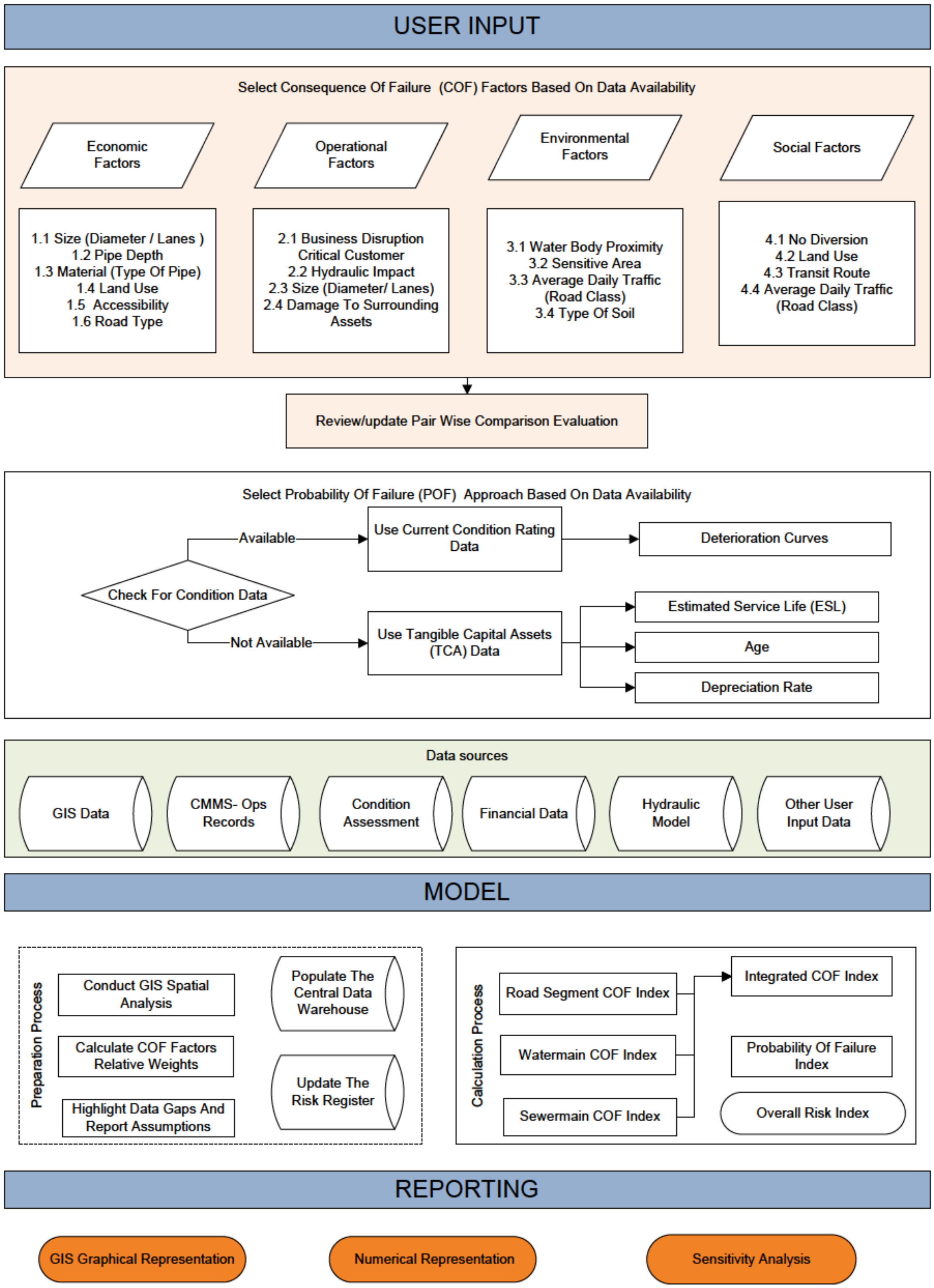


Figure 5-26 IRA Module Process and Data Flow Diagram

Figure 5-27 shows the list of tables within the risk register, and Figure 5-28 show a sample query for the watermains land use

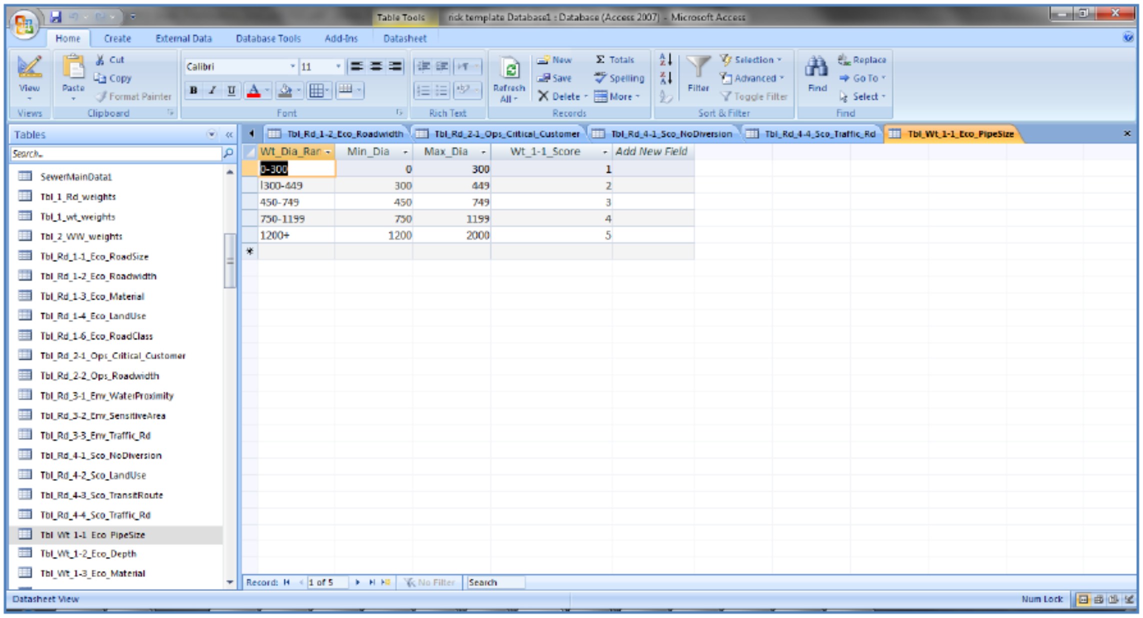


Figure 5-27 List of Tables for the Risk Register

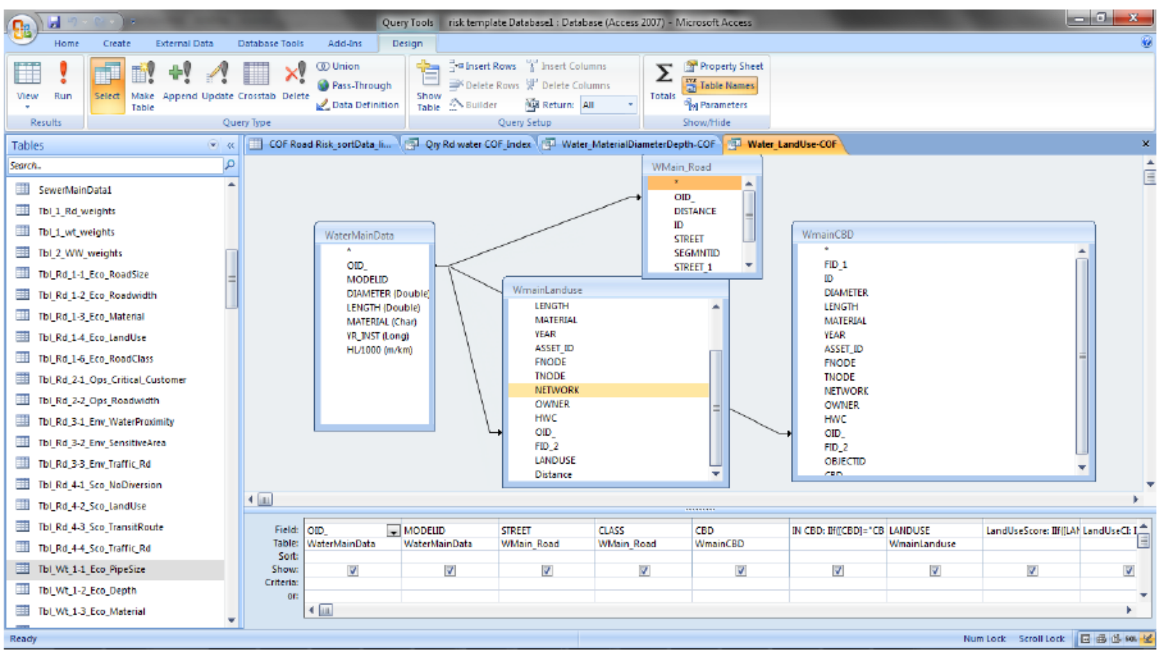


Figure 5-28 Sample Query “Water - Land Use Parameter”

Figure 5-29 underneath shows the SQL script used for the above “Water - land use parameter” query.

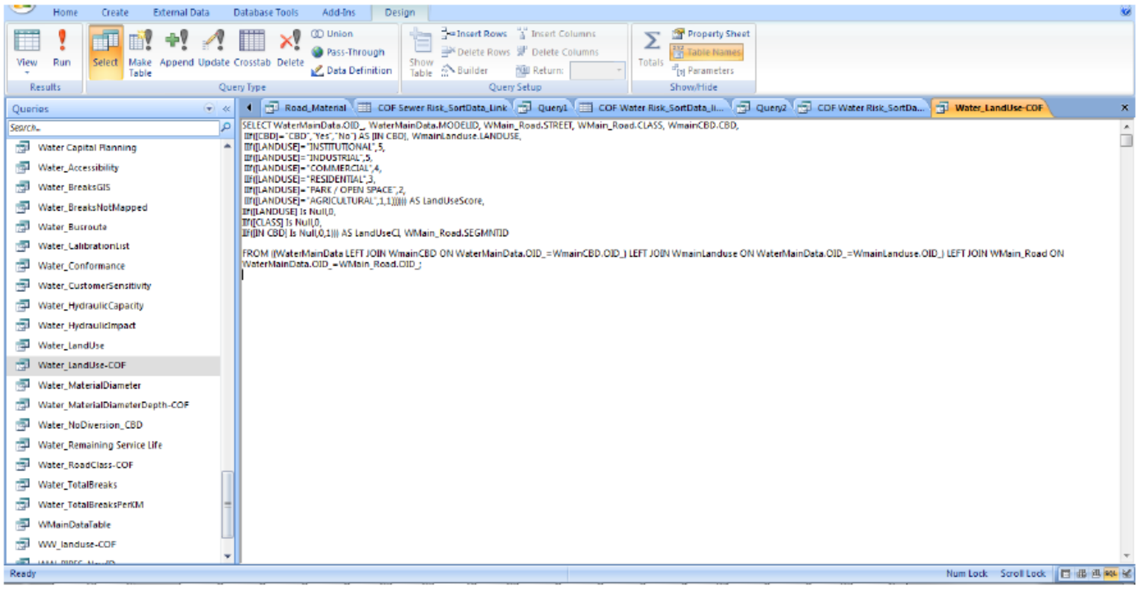


Figure 5-29 SQL Script for “Water - Land Use Parameter” Query

5.4.4 Performance Assessment – CDPM Module

The ultimate goal of all municipalities is to provide an established Level Of Service (LOS) to its customers. These LOS should not only commensurate with the expectations of the customer but also be realistic and practical within the budgetary, timing and external constraints within which the City operates. However, care must be taken to ensure that the definition of the LOS is compatible across all levels of the organization, across all Service Areas, and provides staff at the appropriate level with a relevant and tangible objective which can be influenced by their working practices. The developed Client driven performance measure module provides a structured framework to apply a consistent LOS approach to road, water and sewer assets. Figure 5-30 shows the overall CDPM module process and data flow diagram.

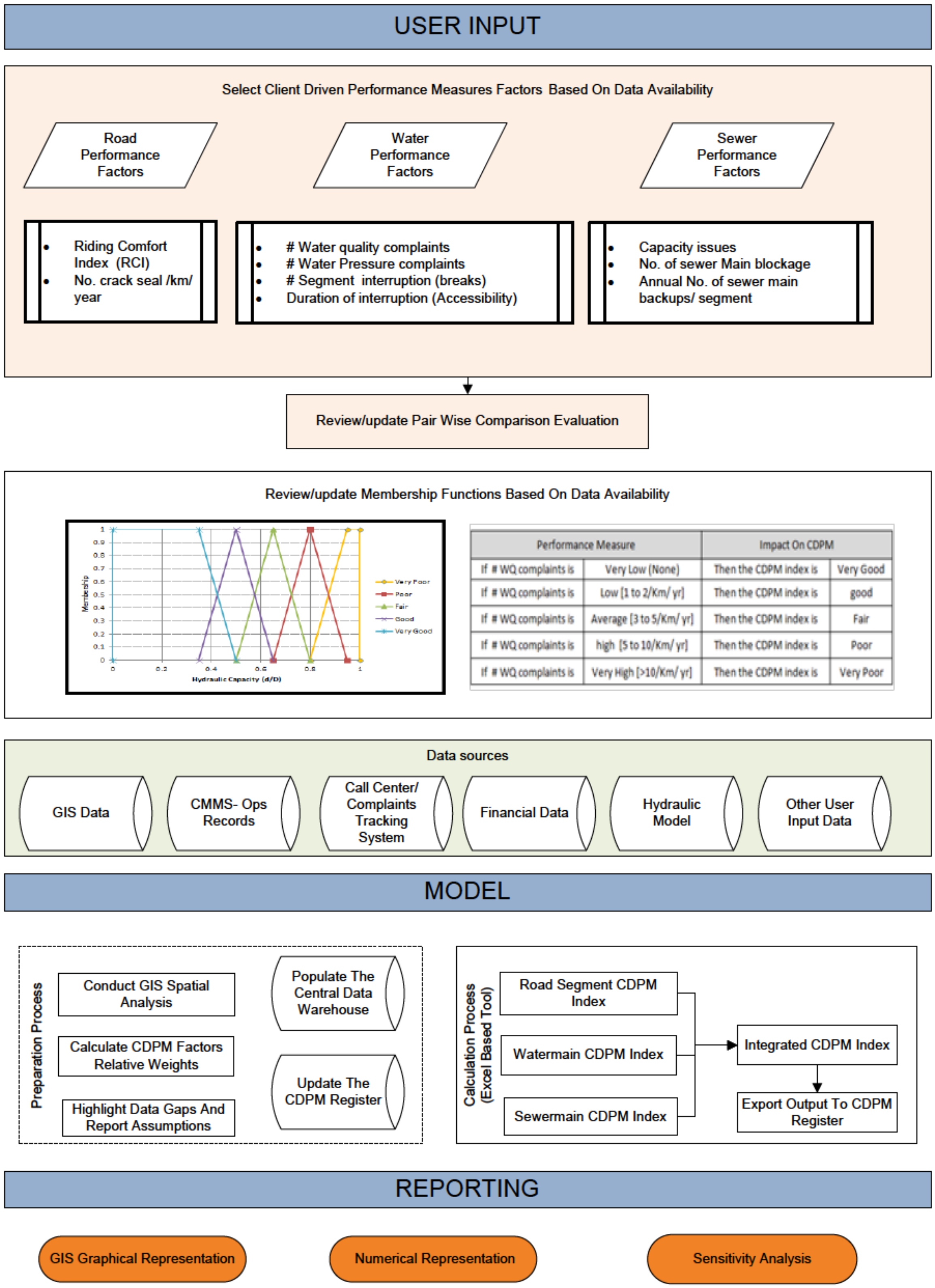
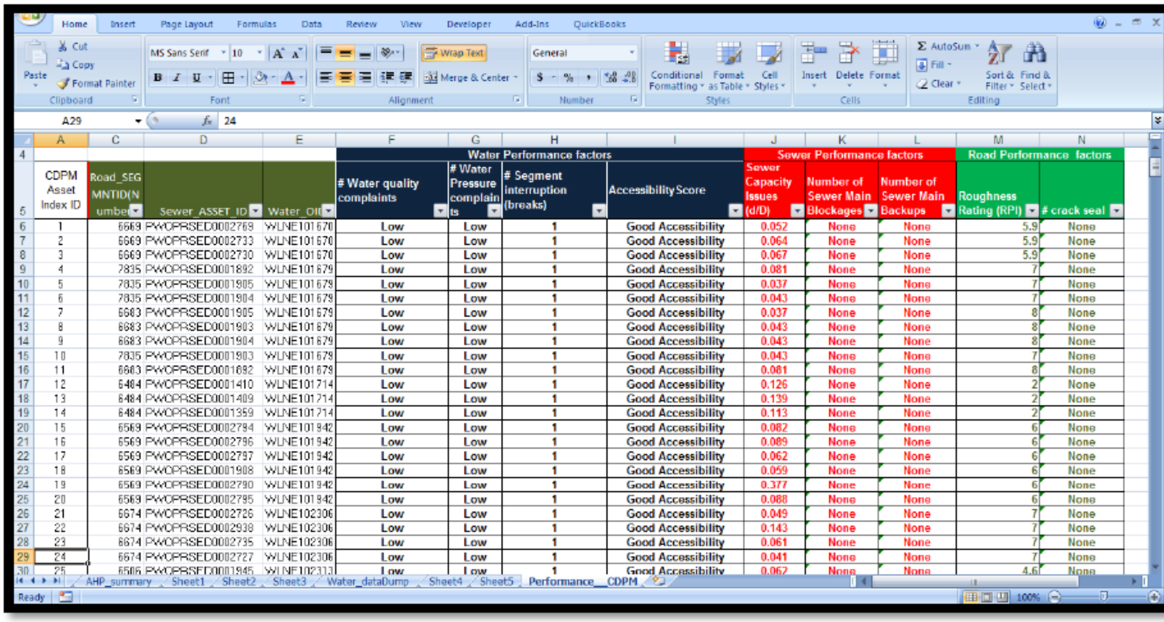


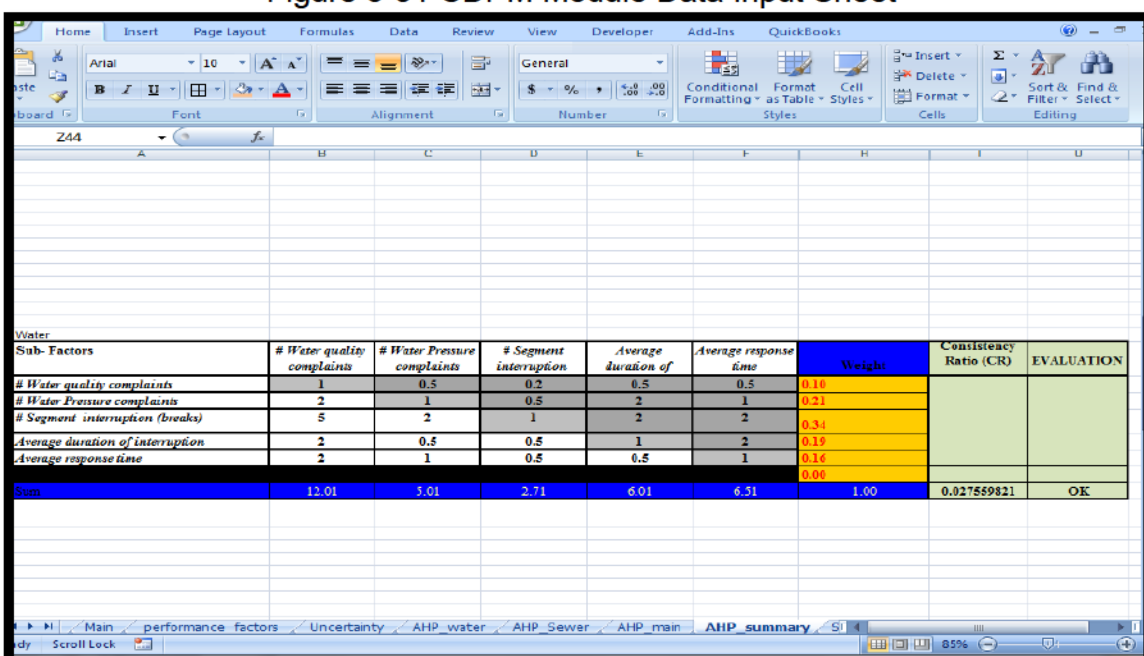
Figure 5-30 CDPM Module Process and Data Flow Diagram

As shown in the Figure 5-30, the Program starts by seeking input from users related to the factors contributing to the performance of asset relative to client/customer expectations. A populated sheet of the data input fields is shown in Figure 5-31.



	CDPM Asset Index ID	Road_SEG MNTID(Number)	Sewer_ASSET_ID	Water_OID	# Water quality complaints	# Water Pressure complaints	# Segment interruption (breaks)	Accessibility Score	Sewer Capacity Issues (d/D)	Number of Sewer Main Blockages	Number of Sewer Main Backups	Roughness Rating (RPI)	# crack seal
4					Water Performance factors				Sewer Performance factors			Road Performance factors	
6	1	6669	PWOPRSED0002769	WLNE101670	Low	Low	1	Good Accessibility	0.052	None	None	5.9	None
7	2	6669	PWOPRSED0002733	WLNE101670	Low	Low	1	Good Accessibility	0.064	None	None	5.9	None
8	3	6669	PWOPRSED0002730	WLNE101670	Low	Low	1	Good Accessibility	0.067	None	None	5.9	None
9	4	7835	PWOPRSED0001892	WLNE101679	Low	Low	1	Good Accessibility	0.081	None	None	7	None
10	5	7835	PWOPRSED0001905	WLNE101679	Low	Low	1	Good Accessibility	0.037	None	None	7	None
11	6	7835	PWOPRSED0001904	WLNE101679	Low	Low	1	Good Accessibility	0.043	None	None	7	None
12	7	6683	PWOPRSED0001905	WLNE101679	Low	Low	1	Good Accessibility	0.037	None	None	8	None
13	8	6683	PWOPRSED0001903	WLNE101679	Low	Low	1	Good Accessibility	0.043	None	None	8	None
14	9	6683	PWOPRSED0001904	WLNE101679	Low	Low	1	Good Accessibility	0.043	None	None	8	None
15	10	7835	PWOPRSED0001903	WLNE101679	Low	Low	1	Good Accessibility	0.043	None	None	7	None
16	11	6683	PWOPRSED0001692	WLNE101679	Low	Low	1	Good Accessibility	0.081	None	None	8	None
17	12	6484	PWOPRSED0001410	WLNE101714	Low	Low	1	Good Accessibility	0.126	None	None	2	None
18	13	6484	PWOPRSED0001409	WLNE101714	Low	Low	1	Good Accessibility	0.139	None	None	2	None
19	14	6484	PWOPRSED0001359	WLNE101714	Low	Low	1	Good Accessibility	0.113	None	None	2	None
20	15	6569	PWOPRSED0002794	WLNE101942	Low	Low	1	Good Accessibility	0.082	None	None	6	None
21	16	6569	PWOPRSED0002796	WLNE101942	Low	Low	1	Good Accessibility	0.089	None	None	6	None
22	17	6569	PWOPRSED0002797	WLNE101942	Low	Low	1	Good Accessibility	0.062	None	None	6	None
23	18	6569	PWOPRSED0001908	WLNE101942	Low	Low	1	Good Accessibility	0.059	None	None	6	None
24	19	6569	PWOPRSED0002790	WLNE101942	Low	Low	1	Good Accessibility	0.377	None	None	6	None
25	20	6569	PWOPRSED0002795	WLNE101942	Low	Low	1	Good Accessibility	0.088	None	None	6	None
26	21	6674	PWOPRSED0002726	WLNE102306	Low	Low	1	Good Accessibility	0.049	None	None	7	None
27	22	6674	PWOPRSED0002938	WLNE102306	Low	Low	1	Good Accessibility	0.143	None	None	7	None
28	23	6674	PWOPRSED0002735	WLNE102306	Low	Low	1	Good Accessibility	0.061	None	None	7	None
29	24	6674	PWOPRSED0002727	WLNE102306	Low	Low	1	Good Accessibility	0.041	None	None	7	None
30	25	6506	PWOPRSED0001945	WLNE102313	Low	Low	1	Good Accessibility	0.062	None	None	4.6	None

Figure 5-31 CDPM Module Data Input Sheet



Water

Sub- Factors	# Water quality complaints	# Water Pressure complaints	# Segment interruption	Average duration of	Average response time	Weight	Consistency Ratio (CR)	EVALUATION
# Water quality complaints	1	0.5	0.2	0.5	0.5	0.10		
# Water Pressure complaints	2	1	0.5	2	1	0.21		
# Segment interruption (breaks)	5	2	1	2	2	0.34		
Average duration of interruption	2	0.5	0.5	1	2	0.19		
Average response time	2	1	0.5	0.5	1	0.16		
						0.00		
Sum	12.01	5.01	2.71	6.01	6.51	1.00	0.027559821	OK

Figure 5-32 AHP Pair Wise Comparison Matrix

Once the CDPM factors are identified, the user can then review the populated AHP pair wise comparisons matrix and update the values as required as illustrated in Figure 5-32 above.

Currently most municipalities do not track customer level of service parameters regularly. The CDPM will enable a more robust information base for business planning and budget process as well as provide tracking tools for client driven performance measures. The CDPM module is designed in a way that enables the decision makers to use the module while collecting the required data for future consideration. The following are the key modifications that will allow the user to effectively utilize the module while having limited amount of data.

- The model allows the user to select from the factors available, based on data availability. (e.g. the user can select only number of breaks and accessibility issues; the pop-up screen allows the selection to be handled automatically, as shown in Figure 5-33.)
- Data input can be used in ranges instead of exact values, to allow for data gaps. If the user selected this approach, the midpoint of that range will be used to calculate the fuzzy membership functions for this range.

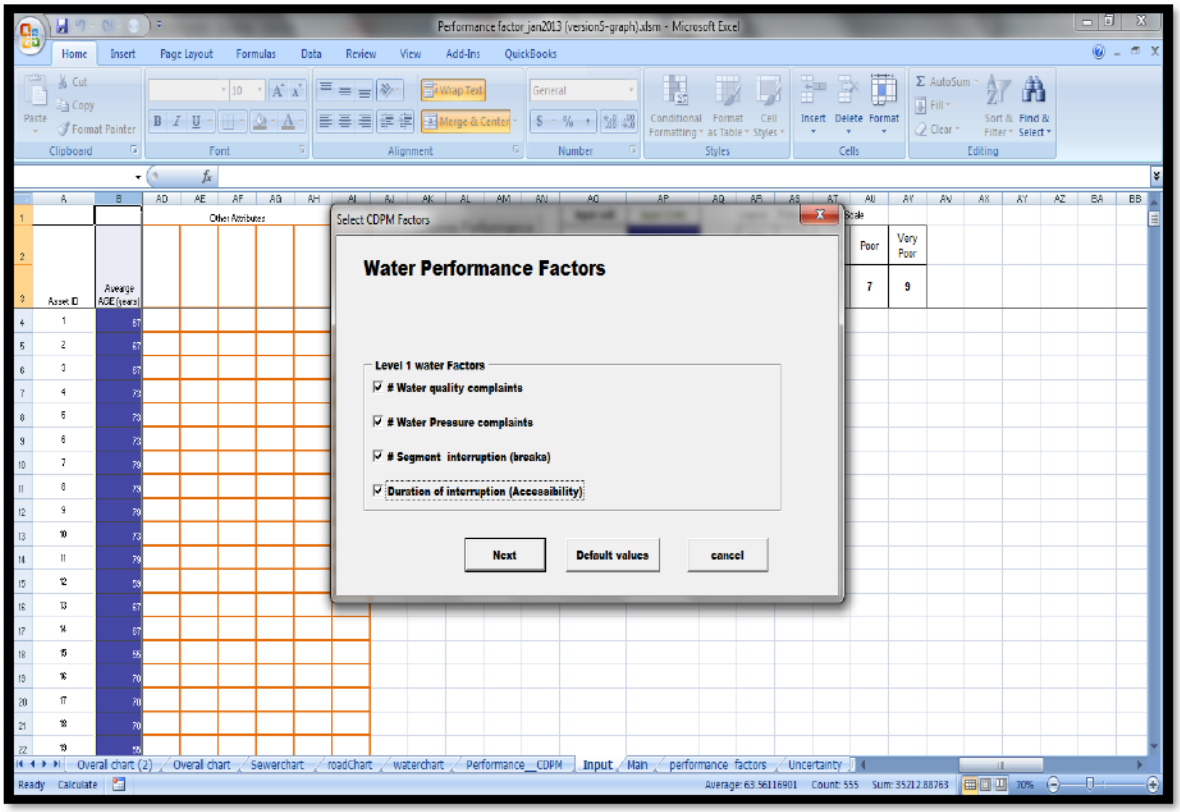


Figure 5-33 CDPM Factor Selection Screen

Similarly, the sewer and road factors can be picked from the checklist. When all the inputs have been entered, the CDPM will automatically run macros to obtain results. This macro calculates the expected CDPM index of the integrated segment and stores the results in the corresponding cell, then calculates the next segment. The model is developed via excel macro and VBA coding. It calculates the minimum, maximum, and expected results for each integrated segment as shown in Figure 5-34. A snapshot of VBA coding for CDPM index is also presented in Figure 5-35.

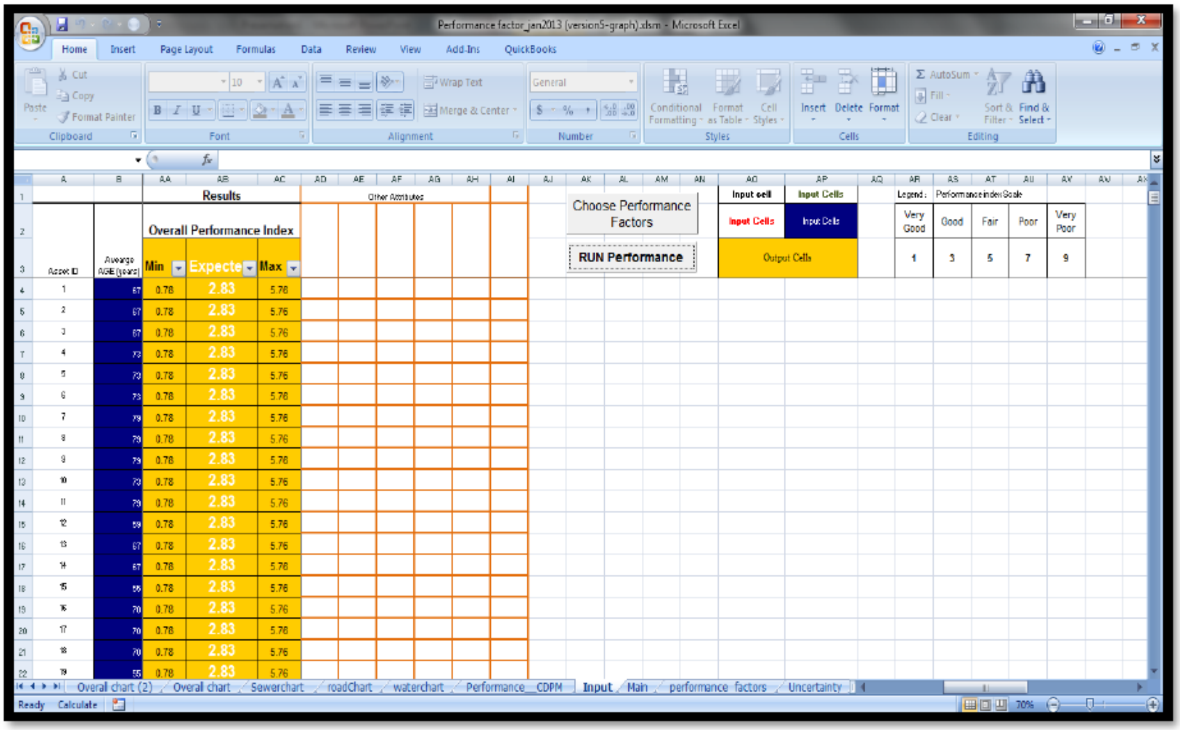


Figure 5-34 CDPM Index Output Results

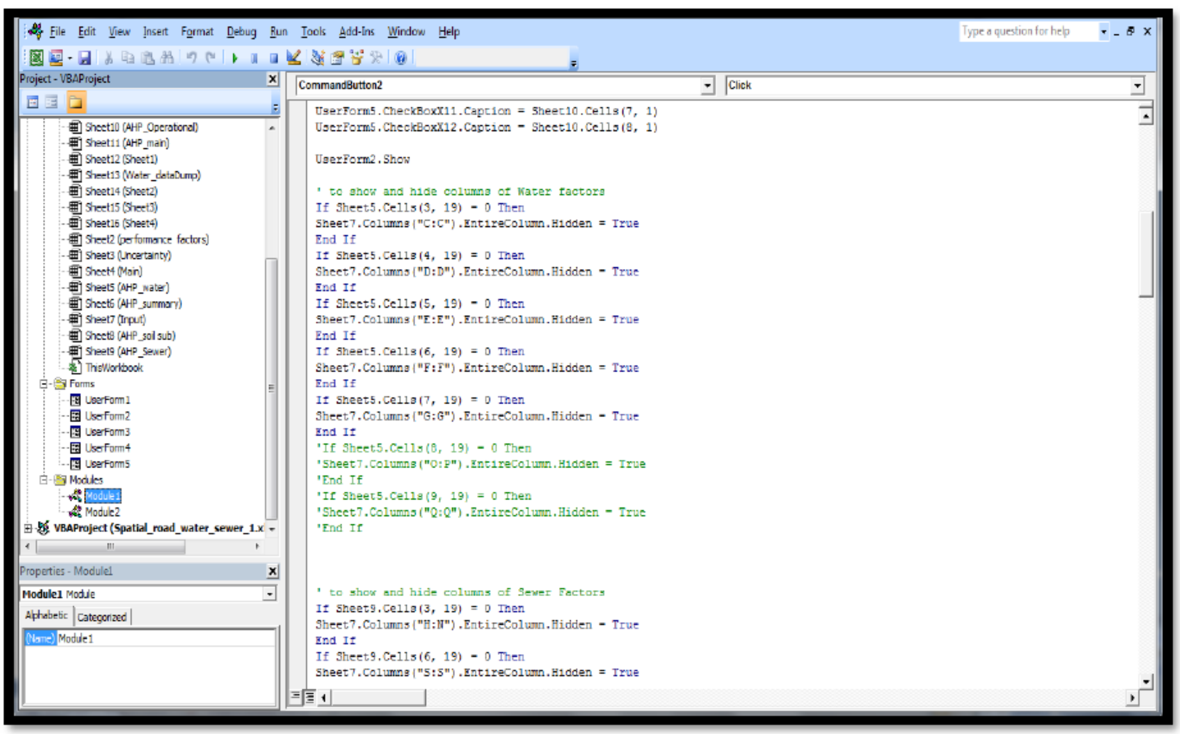


Figure 5-35 CDPM Index VBA Coding Sample

5.4.5 Investment Planning – ODM Module

Within the analysis period, decision makers will determine when the earliest intervention will be required (e.g. water asset is required by next year). Once this timing has been established, IDSS will evaluate the spatially linked assets, assess the decision tree, and select a feasible integration strategy for that timing. No further treatment recommendations are made once the earliest intervention has been established.

Figure 5-36 shows the overall ODM module process and data flow framework. The application development process illustrated is composed of various data sources that serve on all interfaces of the tool. As indicated in this figure, there are mutual relations between the ODM module and the output from both IRA and CDPM Modules. The ODM process starts by analyzing available data for each R/W/S segment. Then the ODM access the central data repository and retrieve all supporting information / attributes. The optimization model utilizes the seven predefined integration alternatives/ options for implementation. ODM model calculates all necessary fields and prompts the user to define the constraints limits and finally recommend the optimal intervention actions. The ODM outputs include GIS representation, numerical report, and sensitivity analysis report.

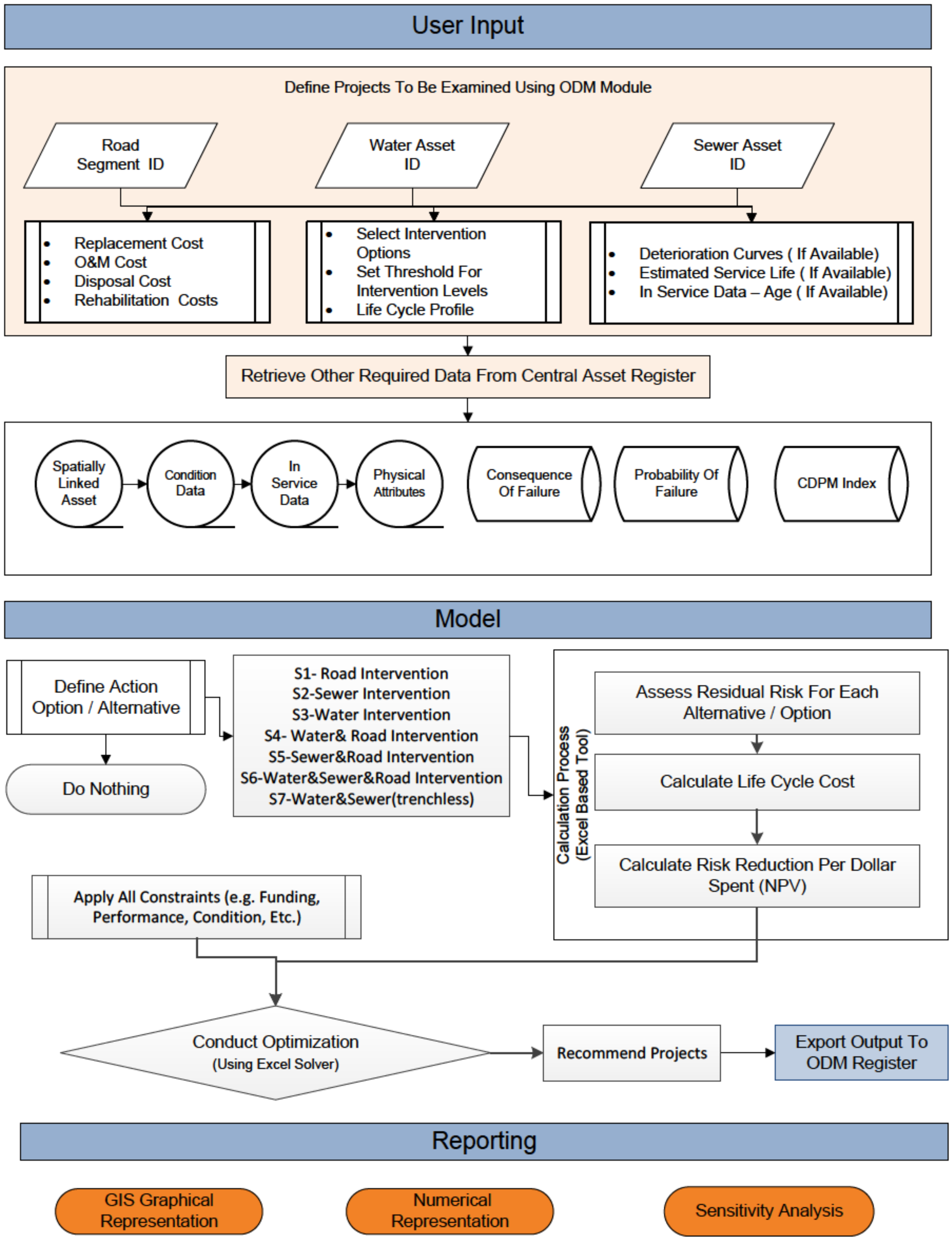
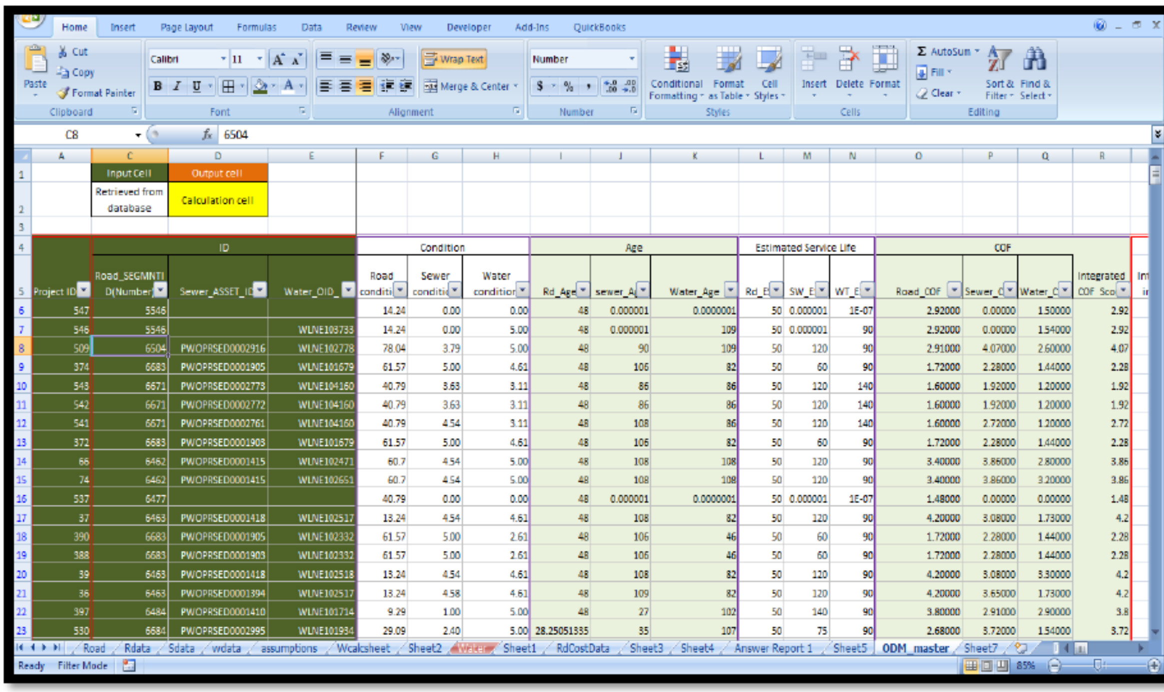


Figure 5-36 ODM Module Process and Data Flow Framework.

The user is directed to the main page shown in Figure 5-37. On this sheet, the required data are arranged for easy selection and introduction (highlighted in green cells). The user has to enter the project No., road segment ID, sewer asset ID, and water asset ID. This information can be directly exported from GIS spatial analysis stage of the process. The ODM automated sheets directly retrieve other required information from the central data repository. Other retrieved information includes Condition, Age, Estimated Service Life (ESL), Consequence of Failure index, CDPM index, etc.



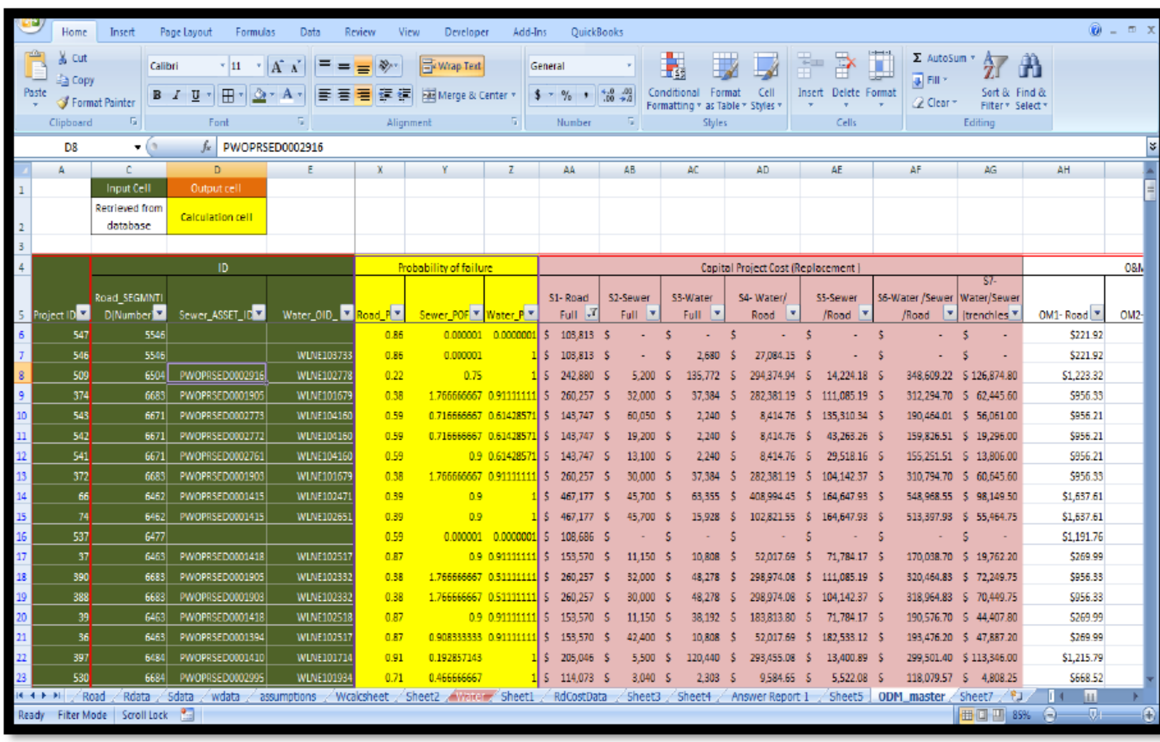
ID				Condition			Age			Estimated Service Life			COF			
Project ID	Road_SEGMNTID(Number)	Sewer_ASSET_ID	Water_OID_	Road conditi	Sewer conditi	Water condition	Rd_Age	sewer_A	Water_Age	Rd_E	SW_E	WT_E	Road_COF	Sewer_C	Water_C	Integrated COF Sco
547	5546			14.24	0.00	0.00	48	0.000001	0.0000001	50	0.000001	1E-07	2.92000	0.00000	1.50000	2.92
546	5546		WLNE103733	14.24	0.00	5.00	48	0.000001	109	50	0.000001	90	2.92000	0.00000	1.54000	2.92
509	6504	PWOPRSED0002916	WLNE102778	78.04	3.79	5.00	48	90	109	50	120	90	2.91000	4.07000	2.60000	4.07
374	6683	PWOPRSED0001905	WLNE101679	61.57	5.00	4.61	48	106	82	50	60	90	1.72000	2.28000	1.44000	2.28
543	6671	PWOPRSED0002773	WLNE104160	40.79	3.63	3.11	48	86	86	50	120	140	1.60000	1.92000	1.20000	1.92
542	6671	PWOPRSED0002772	WLNE104160	40.79	3.63	3.11	48	86	86	50	120	140	1.60000	1.92000	1.20000	1.92
541	6671	PWOPRSED0002761	WLNE104160	40.79	4.54	3.11	48	108	86	50	120	140	1.60000	2.72000	1.20000	2.72
372	6683	PWOPRSED0001903	WLNE101679	61.57	5.00	4.61	48	106	82	50	60	90	1.72000	2.28000	1.44000	2.28
66	6462	PWOPRSED0001415	WLNE102471	60.7	4.54	5.00	48	108	108	50	120	90	3.40000	3.86000	2.80000	3.86
74	6462	PWOPRSED0001415	WLNE102651	60.7	4.54	5.00	48	108	108	50	120	90	3.40000	3.86000	3.20000	3.86
537	6477			40.79	0.00	0.00	48	0.000001	0.0000001	50	0.000001	1E-07	1.48000	0.00000	0.00000	1.48
37	6463	PWOPRSED0001418	WLNE102517	13.24	4.54	4.61	48	108	82	50	120	90	4.20000	3.08000	1.73000	4.2
390	6683	PWOPRSED0001905	WLNE102332	61.57	5.00	2.61	48	106	46	50	60	90	1.72000	2.28000	1.44000	2.28
388	6683	PWOPRSED0001903	WLNE102332	61.57	5.00	2.61	48	106	46	50	60	90	1.72000	2.28000	1.44000	2.28
39	6463	PWOPRSED0001418	WLNE102518	13.24	4.54	4.61	48	108	82	50	120	90	4.20000	3.08000	3.30000	4.2
36	6463	PWOPRSED0001394	WLNE102517	13.24	4.58	4.61	48	109	82	50	120	90	4.20000	3.65000	1.73000	4.2
397	6484	PWOPRSED0001410	WLNE101714	9.29	1.00	5.00	48	27	102	50	140	90	3.80000	2.91000	2.90000	3.8
530	6684	PWOPRSED0002995	WLNE101934	29.09	2.40	5.00	28.25051335	35	107	50	75	90	2.68000	3.72000	1.54000	3.72

Figure 5-37 ODM Input Data Sheet

Once the candidate projects are defined and all other related information is retrieved the ODM module calculates the probability of failure based on the condition data (if available) or age and ESL data as outlined in Section 5.1.3 Probability of Failure.

The user defines the values for the cost data of the selected Asset class or category as summarized in Figure 5-38. Integration rate structures are compiled within the guidelines to replace any integrated segment for road, watermains and sewermains. General cost-sharing criteria with road replacement component are set as follows:

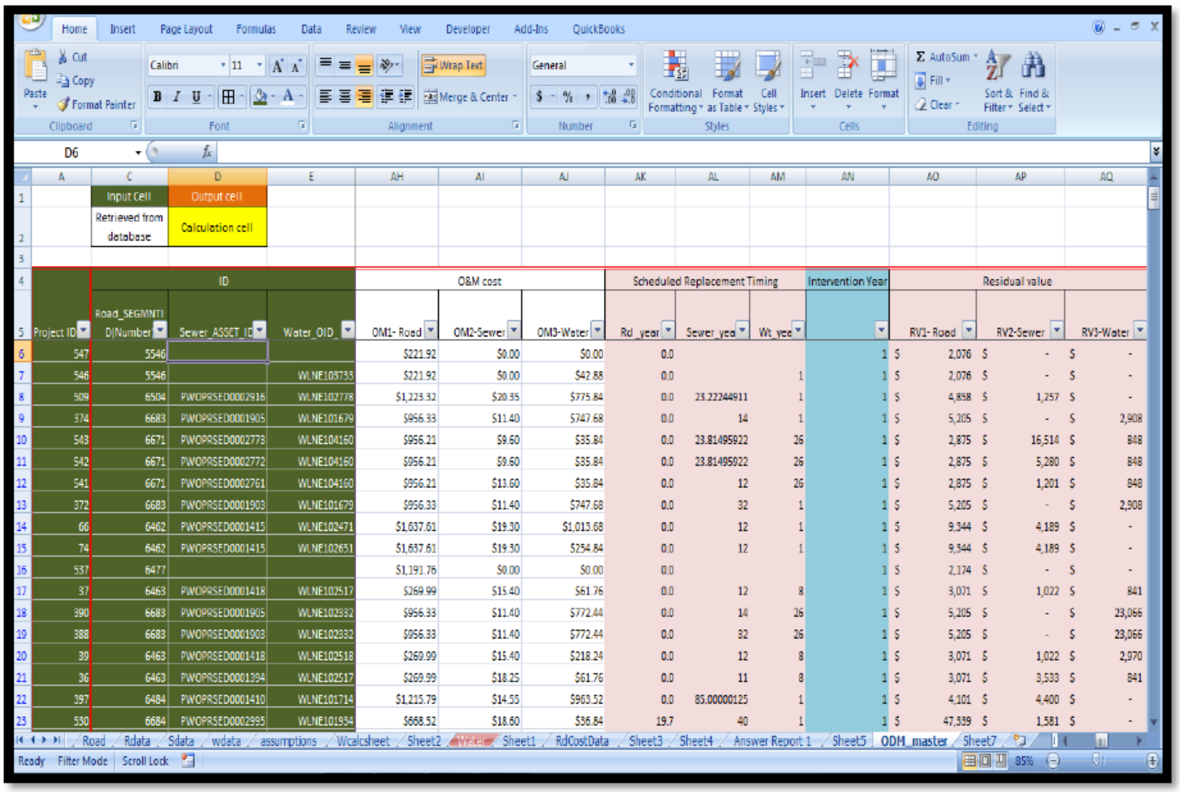
- For combined Water & Sewer project; 50/50% of road restoration cost
- For combined Road & Water project 50/50 % of road restoration cost split between Roads and Water
- For combined Road & Sewer project 50/50 % of road restoration split between Roads and Sewer
- For combined Road & Water & Sewer project 33-33-33% of road restoration split between Roads, Water and Sewer



Project ID	Road_SEGMNTID(Number)	Sewer_ASSET_ID	Water_OID_	Road_P	Sewer_POF	Water_P	S1- Road Full	S2-Sewer Full	S3-Water Full	S4- Water/ Road	S5-Sewer /Road	S6-Water /Sewer /Road	S7- Water/Sewer (trenchles	OM1- Road
547	5546			0.86	0.000001	0.0000001	$ 103,813	$ -	$ -	$ -	$ -	$ -	$ -	$221.92
546	5546		WLNE103733	0.86	0.000001	1	$ 103,813	$ -	$ 2,680	$ 27,084.15	$ -	$ -	$ -	$221.92
509	6504	PWOPRSED0002916	WLNE102778	0.22	0.75	1	$ 242,880	$ 5,200	$ 135,772	$ 294,374.94	$ 14,224.18	$ 348,609.22	$ 126,874.80	$1,223.32
374	6683	PWOPRSED0001905	WLNE101679	0.38	1.766666667	0.91111111	$ 260,257	$ 32,000	$ 37,384	$ 282,381.19	$ 111,085.19	$ 312,294.70	$ 62,445.60	$956.33
543	6671	PWOPRSED0002773	WLNE104160	0.59	0.716666667	0.61428571	$ 143,747	$ 60,050	$ 2,240	$ 8,414.76	$ 135,310.34	$ 190,464.01	$ 56,061.00	$956.21
542	6671	PWOPRSED0002772	WLNE104160	0.59	0.716666667	0.61428571	$ 143,747	$ 19,200	$ 2,240	$ 8,414.76	$ 43,263.26	$ 159,826.51	$ 19,296.00	$956.21
541	6671	PWOPRSED0002761	WLNE104160	0.59	0.9	0.61428571	$ 143,747	$ 13,100	$ 2,240	$ 8,414.76	$ 29,518.16	$ 155,251.51	$ 13,806.00	$956.21
372	6683	PWOPRSED0001903	WLNE101679	0.38	1.766666667	0.91111111	$ 260,257	$ 30,000	$ 37,384	$ 282,381.19	$ 104,142.37	$ 310,794.70	$ 60,645.60	$956.33
66	6462	PWOPRSED0001415	WLNE102471	0.39	0.9	1	$ 467,177	$ 45,700	$ 63,355	$ 408,994.45	$ 164,647.93	$ 548,968.55	$ 98,149.50	$1,637.61
74	6462	PWOPRSED0001415	WLNE102651	0.39	0.9	1	$ 467,177	$ 45,700	$ 15,928	$ 102,821.55	$ 164,647.93	$ 513,397.93	$ 55,464.75	$1,637.61
537	6477			0.59	0.000001	0.0000001	$ 108,686	$ -	$ -	$ -	$ -	$ -	$ -	$1,191.76
37	6463	PWOPRSED0001418	WLNE102517	0.87	0.9	0.91111111	$ 153,570	$ 11,150	$ 10,808	$ 52,017.69	$ 71,784.17	$ 170,038.70	$ 19,762.20	$269.99
390	6683	PWOPRSED0001905	WLNE102332	0.38	1.766666667	0.51111111	$ 260,257	$ 32,000	$ 48,278	$ 298,974.08	$ 111,085.19	$ 320,464.83	$ 72,249.75	$956.33
388	6683	PWOPRSED0001903	WLNE102332	0.38	1.766666667	0.51111111	$ 260,257	$ 30,000	$ 48,278	$ 298,974.08	$ 104,142.37	$ 318,964.83	$ 70,449.75	$956.33
39	6463	PWOPRSED0001418	WLNE102518	0.87	0.9	0.91111111	$ 153,570	$ 11,150	$ 38,192	$ 183,813.80	$ 71,784.17	$ 190,576.70	$ 44,407.80	$269.99
36	6463	PWOPRSED0001394	WLNE102517	0.87	0.908333333	0.91111111	$ 153,570	$ 42,400	$ 10,808	$ 52,017.69	$ 182,533.12	$ 193,476.20	$ 47,887.20	$269.99
397	6484	PWOPRSED0001410	WLNE101714	0.91	0.192857143	1	$ 205,046	$ 5,500	$ 120,440	$ 293,455.08	$ 13,400.89	$ 299,501.40	$ 113,346.00	$1,215.79
530	6684	PWOPRSED0002995	WLNE101934	0.71	0.466666667	1	$ 114,073	$ 3,040	$ 2,303	$ 9,584.65	$ 5,522.08	$ 118,079.57	$ 4,808.25	$668.52

Figure 5-38 Cost Calculation Results for Intervention Options

Timing of intervention is a key component in the optimized decision making process. It is recognized that municipalities generally have some sort of asset management system to determine the future replacement timing of each asset class separately such as Pavement Management System (PMS) for roads. If this information is available it is then utilized within the ODM module, otherwise there is a separate spreadsheet that can conduct this analysis separately. It utilizes life cycle cost analysis for each asset to define the optimal intervention year required for each road, water, and sewer asset as shown in Figure 5-39.



	Input Cell	Output cell											
	Retrieved from database	Calculation cell											
	ID			O&M cost			Scheduled Replacement Timing			Intervention Year	Residual value		
Project ID	Road_SEGMNTID|Number	Sewer_ASSET_ID	Water_OID_	OM1- Road	OM2-Sewer	OM3-Water	Rd_year	Sewer_yea	Wt_yea		RV1- Road	RV2-Sewer	RV3-Water
547	5546			$221.92	$0.00	$0.00	0.0			1	$ 2,076	$ -	$ -
546	5546		WLNE103733	$221.92	$0.00	$42.88	0.0		1	1	$ 2,076	$ -	$ -
509	6504	PWOPRSED0002916	WLNE102778	$1,223.32	$20.35	$775.84	0.0	23.22244911	1	1	$ 4,858	$ 1,257	$ -
374	6683	PWOPRSED0001905	WLNE101679	$956.33	$11.40	$747.68	0.0	14	1	1	$ 5,205	$ -	$ 2,908
543	6671	PWOPRSED0002773	WLNE104160	$956.21	$9.60	$35.84	0.0	23.81495922	26	1	$ 2,875	$ 16,514	$ 848
542	6671	PWOPRSED0002772	WLNE104160	$956.21	$9.60	$35.84	0.0	23.81495922	26	1	$ 2,875	$ 5,280	$ 848
541	6671	PWOPRSED0002761	WLNE104160	$956.21	$13.60	$35.84	0.0	12	26	1	$ 2,875	$ 1,201	$ 848
372	6683	PWOPRSED0001903	WLNE101679	$956.33	$11.40	$747.68	0.0	32	1	1	$ 5,205	$ -	$ 2,908
66	6462	PWOPRSED0001415	WLNE102471	$1,637.61	$19.30	$1,013.68	0.0	12	1	1	$ 9,344	$ 4,189	$ -
74	6462	PWOPRSED0001415	WLNE102651	$1,637.61	$19.30	$254.84	0.0	12	1	1	$ 9,344	$ 4,189	$ -
537	6477			$1,191.76	$0.00	$0.00	0.0			1	$ 2,174	$ -	$ -
37	6463	PWOPRSED0001418	WLNE102517	$269.99	$15.40	$61.76	0.0	12	8	1	$ 3,071	$ 1,022	$ 841
390	6683	PWOPRSED0001905	WLNE102332	$956.33	$11.40	$772.44	0.0	14	26	1	$ 5,205	$ -	$ 23,066
388	6683	PWOPRSED0001903	WLNE102332	$956.33	$11.40	$772.44	0.0	32	26	1	$ 5,205	$ -	$ 23,066
39	6463	PWOPRSED0001418	WLNE102518	$269.99	$15.40	$218.24	0.0	12	8	1	$ 3,071	$ 1,022	$ 2,970
36	6463	PWOPRSED0001394	WLNE102517	$269.99	$18.25	$61.76	0.0	11	8	1	$ 3,071	$ 3,533	$ 841
397	6484	PWOPRSED0001410	WLNE101714	$1,215.79	$14.55	$963.52	0.0	85.00000125	1	1	$ 4,101	$ 4,400	$ -
530	6684	PWOPRSED0002995	WLNE101934	$668.52	$18.60	$36.84	19.7	40	1	1	$ 47,339	$ 1,581	$ -

Figure 5-39 ODM Module Screen Shot for Timing of Interventions

Following the development of timing of interventions, assessing risk, and assessing CDPM, the Projects can be ranked by biggest risk reduction per dollar spent. Then, those projects that will give the largest overall movement in risk for a set funding allocation can be addressed as opposed to spending all of the available funding just mitigating the highest risks. The proposed risk based decision making approach is summarized in Section 5.1 Integrated Risk Model Development. Screen shots for the calculated risk reduced per dollar spent is shown in Figure 5-40.

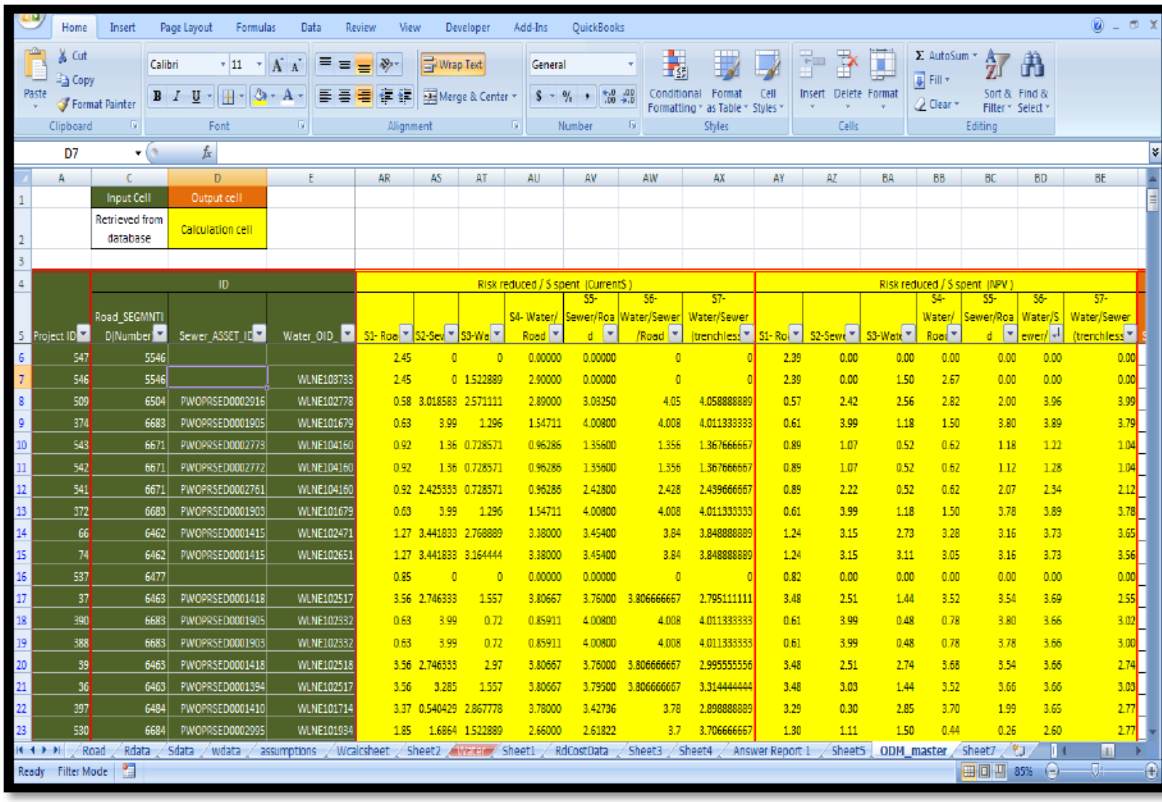


Figure 5-40 Risk Reduced Per Dollar Spent Calculation

Apply all constraints such as funding level, minimum acceptable Level of service, performance, condition. Then check that assets at major risk are included in the recommended intervention list. Then conduct optimization using Excel solver. Figure 5-41 Show the optimization formulation screen shot.

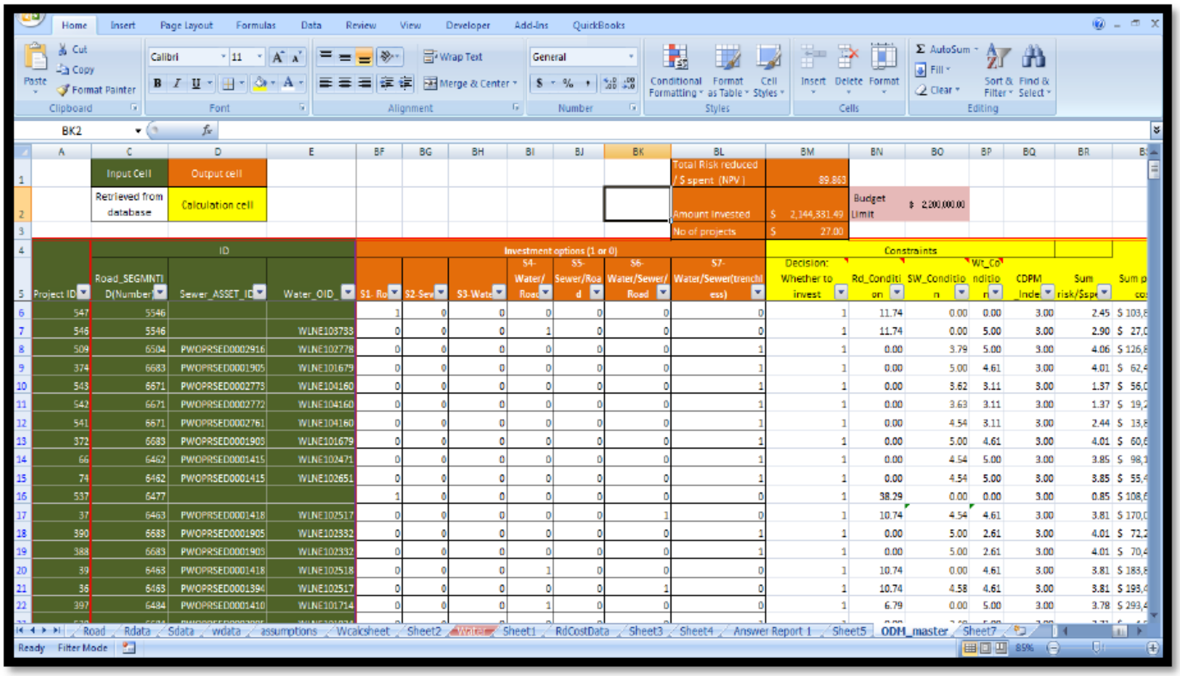


Figure 5-41 ODM Module-Optimization Screen

Then, run Excel solver as shown in Figure 5-42. Once the model solves the optimization problem, it summarizes recommended investment/projects.

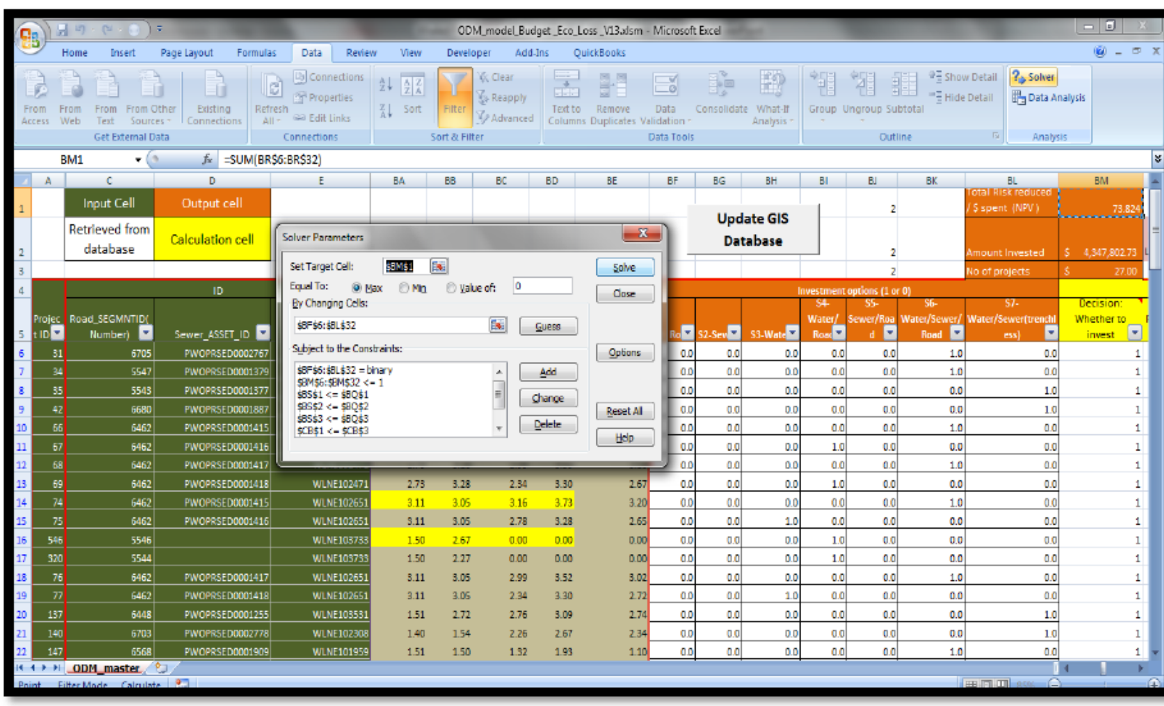


Figure 5-42 Excel Solver Screen Shot

5.5 Summary

This chapter covered the integrated decision support system development. It includes three models:

An Integrated Risk Assessment (IRA) model is developed to predict and assess the probability of failure and consequence of failure of an integrated road segment, watermain, and sewermain asset. Eighteen factors within four main parameters (economic, environmental, operational, and social impacts) are used to represent the consequence of failure assessment process. The next step was to calculate the relative weight of each factor within each consequence of failure parameters using a Delphi – AHP process. Results show that pipe/ road size have the highest effect on overall Consequence of Failure index (11.7%), then Accessibility (10.9%); however, the third factor is Environmental Sensitive Area (9.9%). The probabilities of failure were established based on existing condition information and then assigned a probability of failure value between (0.01-1). "K-mean" clustering using its unsupervised learning algorithms was conducted to calculate the integrated risk assessment of each segment.

Secondly a Client/ Customer Driven Performance Measure (CDPM) model is developed to assess the customer level of service performance of an integrated road segment, watermain, and sewermain asset. Nine customer performance measures are used to represent the CDPM assessment process. The next step was to establish the fuzzy membership functions for each performance measure. Then, it is necessary to build the rule base between input and the output. Results showed that road *Roughness Rating (RPI) has the* *highest impact on CDPM index followed by number of watermain interruption (breaks) then Sewermain Capacity issues.* The third developed model was the optimized decision-making (ODM) model of various integration options. This optimization model was developed using integer-programming algorithm. The optimization objective is to maximize the risk reduction for minimum net present value of investment cost subject to condition, CDPM and budget constraints.

The last section in this chapter presented the prototype tool “Integrated Decision Support System” (IDSS) development and implementation. The IDSS was developed using the visual basic applications (VBA) programming and was implemented as a set of applications that are Access and excel based. The developed system applications were designed to be easily linked to Esri Arc-GIS for geographical representation. The developed system architecture is composed of three modules and a central asset registry database. As discussed above, each module contains some processes and there are some mutual relations between the modules, which illustrate how they are linked together..

CHAPTER 6: INTEGRATED ASSET MANAGEMENT MODEL IMPLEMENTATION AND RESULTS

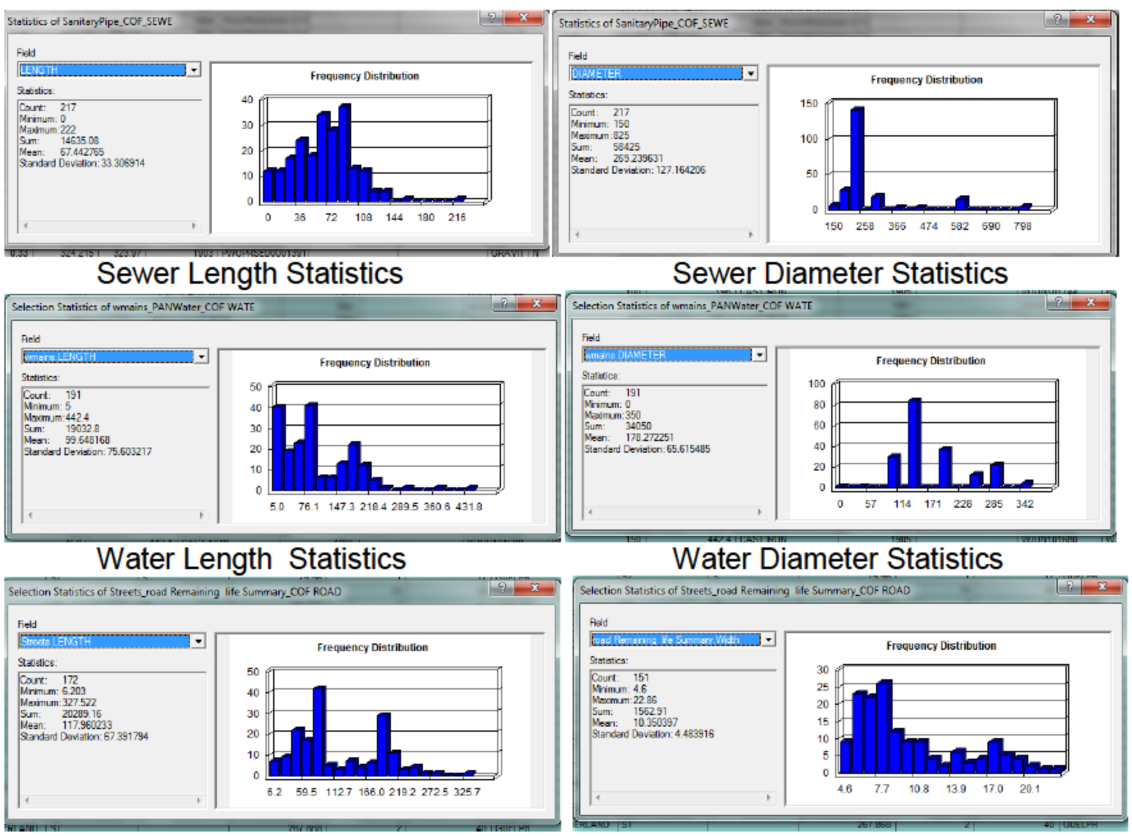
In order to demonstrate that the proposed methodology can function effectively in handling the optimization problem, a numerical experiment is conducted based on the sub network of the city of Guelph. Table 6-1 outlines the major data sources used by the integrated decision support system model. The full list of attributes required is available in Appendix C

Table 6-1 IDSS Model Major Data Sources

Data sources	Description	Database Format
Geo-database / GIS shape files	This is a map based data source for road , water and sewer	GIS
CMMS	Computerized Maintenance Management System; this data is stored in various maintenance management systems; excel base files or hard copy files.	Access , Excel , Hardcopy
Condition Assessment Records	Road data is stored in Roadmatrix database, sewer data is stored in SAWS database, and water data is stored in WCAP database (e.g. WRC Code, PQI, Imminent failure, Failure modes, Condition score, Poor, Fair, Bad, etc.)	Access , Excel , Hardcopy
Financial data	This includes replacement cost, Historical Cost-TCA , work order linked to assets, Direct Costs – Labour, Indirect Costs, depreciation method, book value, account payable, etc. (stored in JDE financial system)	JDE-Access database
Hydraulic model	Data is stored in info water and info sewer database	Info AM-Access database
Budget documents	Capital & Operating maintenance projections for infrastructure assets	Hardcopy , Excel
Miscellaneous Spreadsheets	Almost all groups rely on an array of spreadsheets to track specific asset attribute information and support their business process	Excel

The data provided by the city needed some manipulation to be able to use it for the IDSS model implementation. The first step is to spatially link the three separate GIS shape files (R/W/S), using the approach described in chapter 3 to be able to transfer data between asset classes. A sub network of the city of Guelph GIS network was selected to apply the developed tools on it. Figure 6-1 shows the sample network data characteristic, while Figure 6-2 depicts the spatial analysis for this sub network.

	Number of segments	Total length
Road Network	172	~20 km
Water Network	201	~19 km
Sewer Network	217	~14 km
R/W/S Combined Alternatives	554	N/A



Sewer Length Statistics | Sewer Diameter Statistics

Water Length Statistics | Water Diameter Statistics

Road Length Statistics | Road Width Statistics

Figure 6-1 Summary of Statistical Analysis for the Selected Sub Network

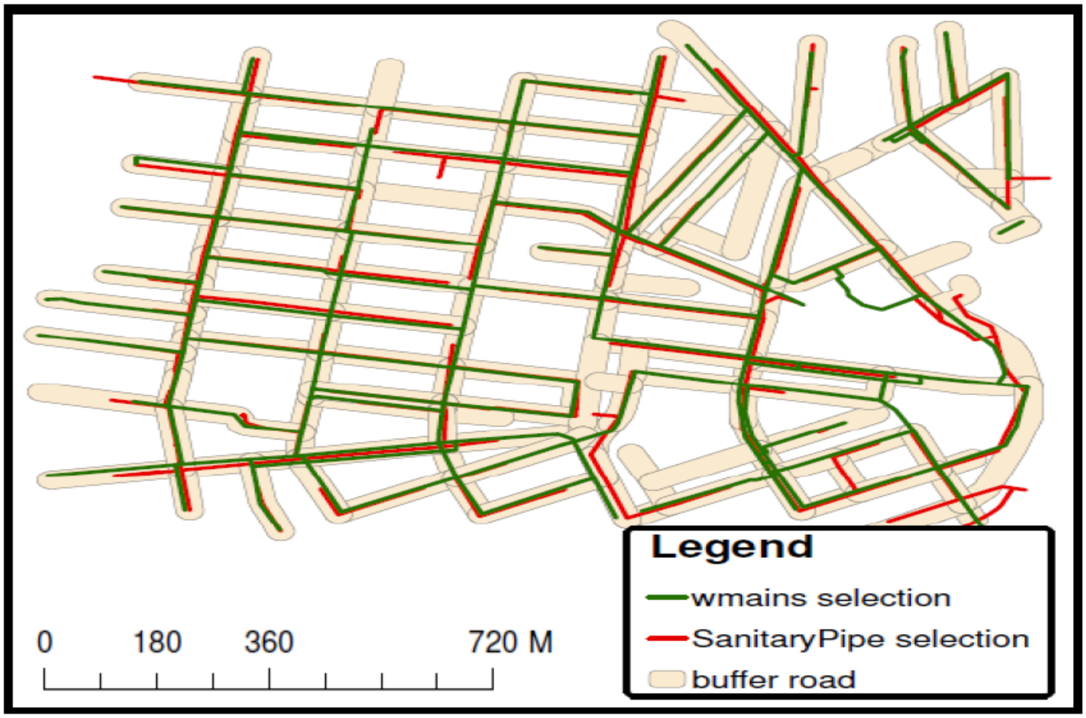


Figure 6-2 Spatial Analysis for the Selected Sub Network

6.1 Integrated Risk Model Results

The risk model relies on integrating attributes relating to the road, watermain, and sewermain and its surroundings to provide a measure for risk based on economic, operational, social, and environmental considerations. These attributes used to develop this risk model are a combination of direct attributes stored in the Geodatabase tables (e.g. road size, diameter, depth, type, etc…), as well as attributes from other sources (e.g. land use, location of critical customers, etc…). Storing all required attributes in a central data repository will facilitate the model development and implementation. A criticality matrix for road, sewers, and water assets was developed using the data collected from the case study. The tool runs on a GIS platform to query and calculate the criticality score to prioritize the assets in terms of their consequences of failure. The GIS enables asset managers to generate maps identifying areas of concerns to prioritize operating and capital construction funding. The results of water Delphi-Analytical Hierarchy Process matrices are shown in Table 6-2. It was noted that not all data was available for the selected case study, as such the missing factors (e.g. utility locations, soil types in some areas) were assigned an overall weight of zero and the AHP weights for the other factors were recalculated.

Table 6-2 Consequence of Failure Factors Weights (Case Study)

Main Factor	**Sub-Factor**	Weight ($W_{index\ i}$ & $W_{Var\ ij}$)	Decomposed weight (*SWij*)
1. Economic Index		**0.39**	
Economic	1.1 *Pipe Size (Diameter)*	0.19	0.0741
Economic	1.2 Pipe Depth	0.21	0.0819
Economic	*1.3 Material (Type of Pipe)*	0.16	0.0624
Economic	*1.4 Land Use*	0.06	0.0234
Economic	1.5 Accessibility	0.28	0.1092
Economic	1.6 Road type	0.1	0.0390
2.0 Operational Index		**0.27**	
Operational	2.1 Business Disruption Critical Customer	0.39	0.1053
Operational	2.2 Hydraulic Impact	0.34	0.0918
Operational	2.3 *Pipe Size (Diameter)*	0.27	0.0729
Operational	2.4 Damage to surrounding Assets[2]	0.00	0.0000
3.0 Environmental Index		**0.21**	
Environmental	*3.1 Water body proximity*	0.20	0.0420
Environmental	3.2 Sensitive Area	0.54	0.1134
Environmental	3.3 *Average Daily Traffic (Road Class)*	0.26	0.0546
Environmental	*3.4 Type of Soil*[2]	0.00	0.0000
4.0 Social Index		**0.13**	
Social	4.1 No Diversion	0.40	0.0520
Social	*4.2 Land Use*	0.10	0.0130
Social	4.3 Transit Route	0.20	0.0260
Social	4.4 *Average Daily Traffic (Road Class)*	0.30	0.0390
		Sum	**1.00**

[2] Data was not available

Each Consequence of Failure parameter has various variables / attributes in which they are not similar in their effect on consequence of failure. Table 6-3 summarizes the watermains factors. It shows the economic and operational parameters. Additionally it presents the data processing approach used to assign COF scores to each watermain segment. Similarly, Table 6-4 shows the data processing approach for environmental and social parameters.

Table 6-3 Data Processing - Economic and Operational Parameters

Factors	Data Processing Notes
1. Economic Parameters	
1.1 *Pipe Size (Diameter)*	None
1.2 Pipe Depth	None
1.3 Material (Type of Pipe)	Pipe materials were obtained from the water hydraulic model and GIS
1.4 Land Use	Land use classifications must be assigned to each pipe. Therefore, Spatial intersect with 20m buffer zone around Land use and central business district shape files provided by the City were spatially assigned to the watermains.
1.5 Accessibility	A list of pipes with marginal and low accessibility was obtained from the City.
1.6 Road type	Conducted a GIS Spatial intersection with roads shape files.
2.0 Operational Parameters	
2.1 Business Disruption Critical Customer	The City provided a list of customers from their priority service database which was then spatially joined with the watermain and attributed to individual pipes
2.2 Hydraulic Impact	Hydraulic Impact is defined as the probability of satisfying nodal demands and minimum pressures for possible pipe failures in the water distribution system. InfoWater Protector breaks each pipe one at a time to determine the effect on the system. Pipes are assigned a status of pass or fail depending on the hydraulic impact a failure would have on the system. Hydraulic Impact scores based on the results from water Hydraulic model (InfoWater Protector) were assigned.
2.3 *Pipe Size (Diameter)*	None
2.4 *Damage to surrounding Assets*	This factor is used to quantify the impact of failure on the surrounding infrastructure including, gas, utilities, cables, electricity, etc. Municipalities do not typically own these assets; data was not available for this parameter.

Table 6-4 Data Processing - Environmental and Social Parameters

Factors	Data Processing Notes
3.0 Environmental Parameters	
3.1 Water body proximity	Conducted a GIS-Spatial intersection with rivers and lake areas are performed to assign these scores.
3.2 Sensitive Area	Conducted a GIS-Spatial intersection with watershed and environmental areas
3.3 *Average Daily Traffic (Road Class)*	Conducted a GIS Spatial intersection with street centerline that is buffered by value of road width
3.4 Type of Soil	Data was not available.
4.0 Social Parameters	
4.1 No Diversion	Conducted a GIS-Spatial intersection with road centerlines that are buffered by road width and are determined to have no diversion
4.2 Land Use	Land use classifications must be assigned to each pipe. Therefore, Spatial intersect with 20m buffer zone around Land use and central business district shape files provided by the City were spatially assigned to the watermains.
4.3 Transit Route	Conducted a GIS Spatial intersection with road centerlines that are buffered by road width and are determined to have transit route.
4.4 *Average Daily Traffic (Road Class)*	Conducted a GIS Spatial intersection with street centerline that is buffered by value of road width

Probability of failure was established based on the current condition assessment and deterioration curves used by the city. The following sections provide examples for road and sewer infrastructure condition rating metrics, applied for a sub network of the City of Guelph assets, used to estimate the probability of failure.

- ***Road Network Condition***

The pavement condition rating evaluation consists of a pavement distress survey, and the calculation and reduction of data into a surface condition scale through Pavement Management Application software. Stantec's RT-3000 data collection vehicle was used to complete field data collection component on the paved roads. More specifically, this unit surveyed the paved network and collected pavement distress, road roughness, and digital video data. The Pavement Management System (PMS) database contains pavement rehabilitation historical data which include information on all types of previous treatments, their application date, and associated costs. Figure 6-3 shows a sample of the road condition rating results for city of Guelph, ON.

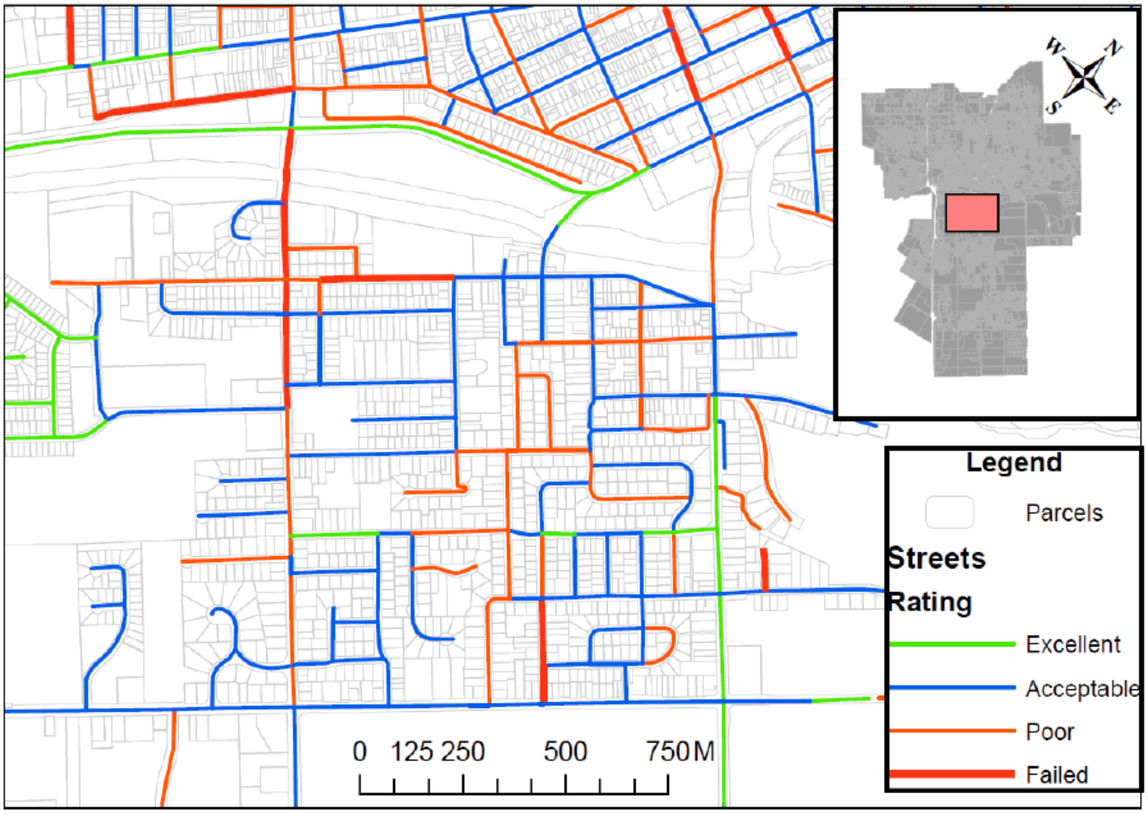


Figure 6-3 Sample Road Segments Condition Rating (Shahata and Zayed, 2009)

- ***Sewer Network Condition***

The WRc rating system and operator/inspector certification provides for a consistent assessment of the structural condition both across individual catchments and between different catchments. The intent of the condition assessment process is to attach a condition grade to each reach of sewer based on the worst defect in that reach. This is a two step process involving the assignment of a preliminary internal condition grade (ICG) based on the raw defect scores obtained from CCTV inspections using the WRc rating system. Table 6-5 shows how to assign a numeric value to each defect to produce an overall Internal Condition Grade. The condition grades are broken down into five categories, or discrete condition states, based on the potential for collapse and the likelihood of further deterioration. A final performance grade, or Structural Performance Grade (SPG), is then assigned based on the consideration of supplementary data such as soil conditions (if available), frequency of surcharging and cursory data as shown in Figure 6-4. SPG is assigned by qualified inspector (NAPPI / NASSCO certified) based on the impact/ significance of observed defects on performance. Grades reflect the Probability of Collapse where 1 (pristine) to 5 (collapsed or collapse is imminent). Figure 6-5 shows a sample sewermains condition rating results for city of Guelph, ON.

Table 6-5 Sewer Defect Scores (adapted from WRC (2001))

DEFECT	DESCRIPTION	SCORE	UNIT
Open Joint	Slight Medium Large	1 2 165	per joint per joint per joint
Displaced Joint	Slight Medium Large	1 2 80	per joint per joint per joint
Cracked	Circumferential Longitudinal Multiple	10 10 40	per crack per crack each
Fractured	Circumferential Longitudinal Multiple	40 40 80	per fracture per fracture each
Broken	–	80	each
Deformed	0 - 5% 5 - 10% 10% +	20 80 165	each each each
Hole	< ¼ Circumference > ¼ Circumference	80 165	each each
Collapsed	–	165	each

Computed ICG	Peak Score
1	< 10
2	10 – 39
3	40 – 79
4	80 – 164
5	165 +

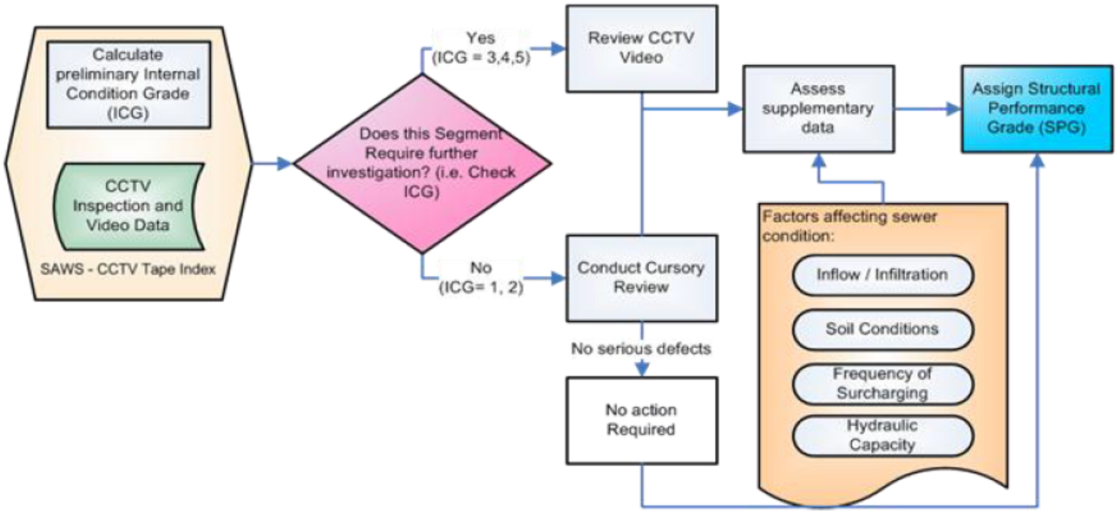


Figure 6-4 Sewer Structural Performance Assessment Procedure (Shahata and Zayed, 2010)

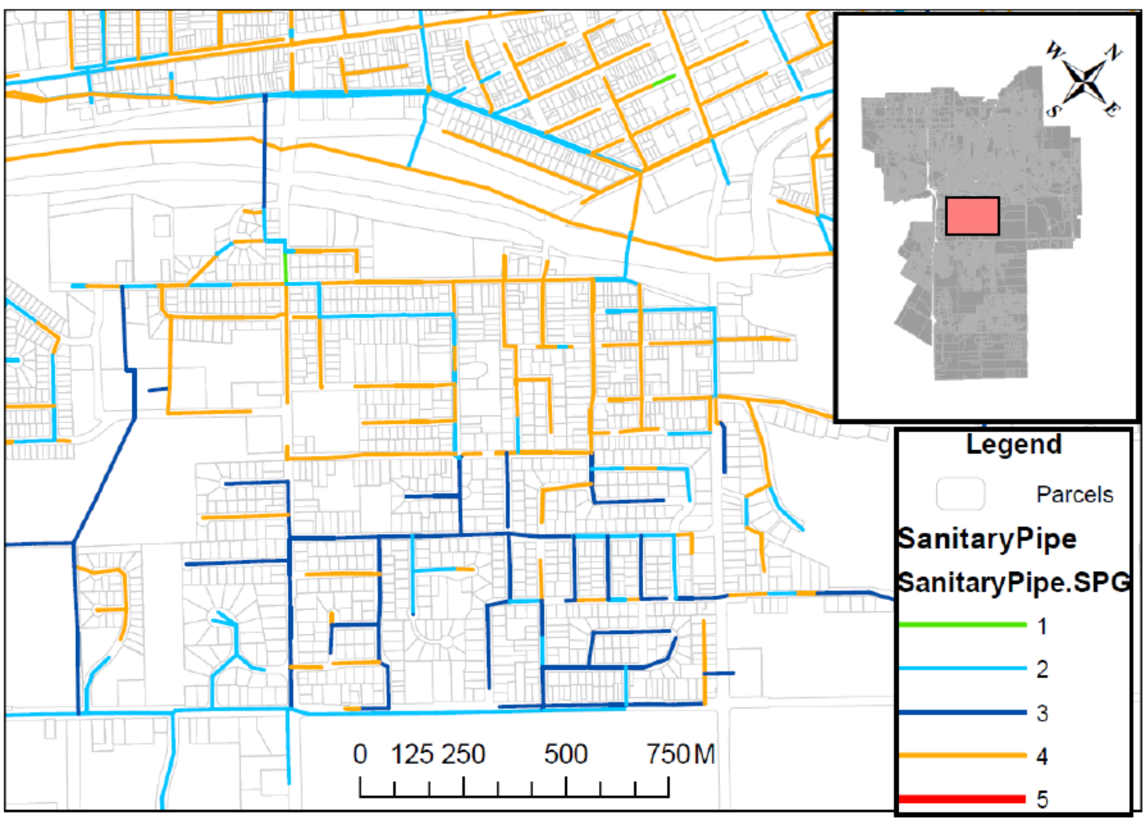


Figure 6-5 Sample Sewermains Condition Rating (Shahata and Zayed, 2009)

Figure 6-6 shows an Overview of City of Guelph integrated risk index results for road, water and sewer network. Additionally, Figure 6-7, Figure 6-8 and Figure 6-9 show a sample of Risk Model results for road, water and sewermains respectively.

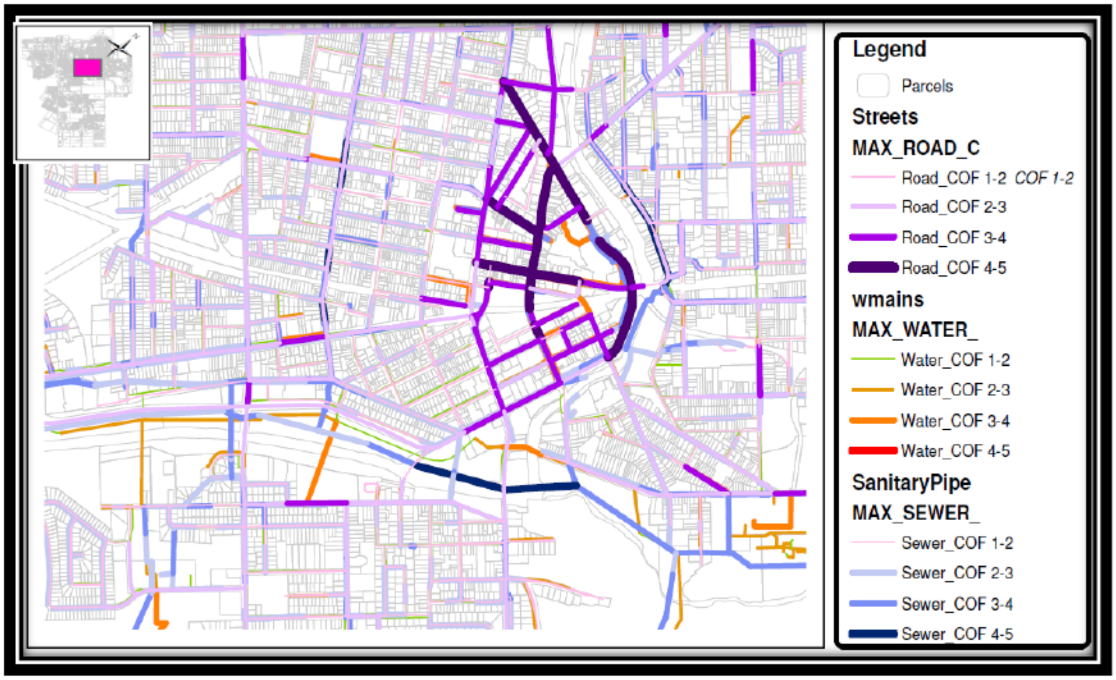


Figure 6-6 City of Guelph Integrated Risk Index Results

Figure 6-7 City of Guelph Integrated Risk Index Results for Watermains

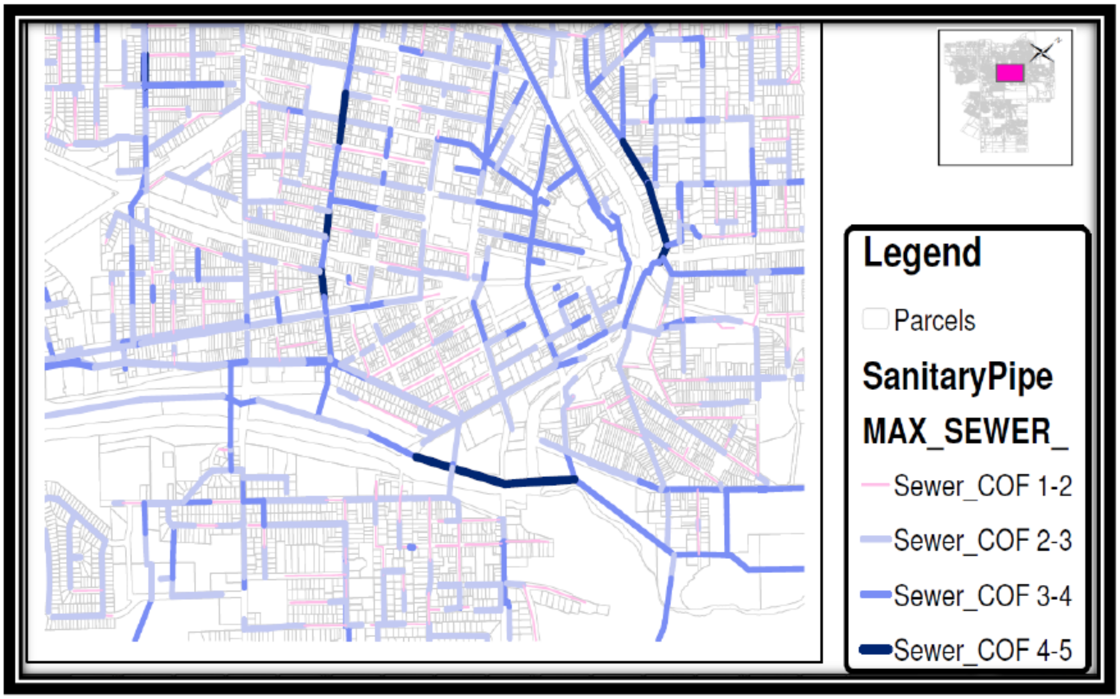


Figure 6-8 City of Guelph Integrated Risk Index Results for Sewermains

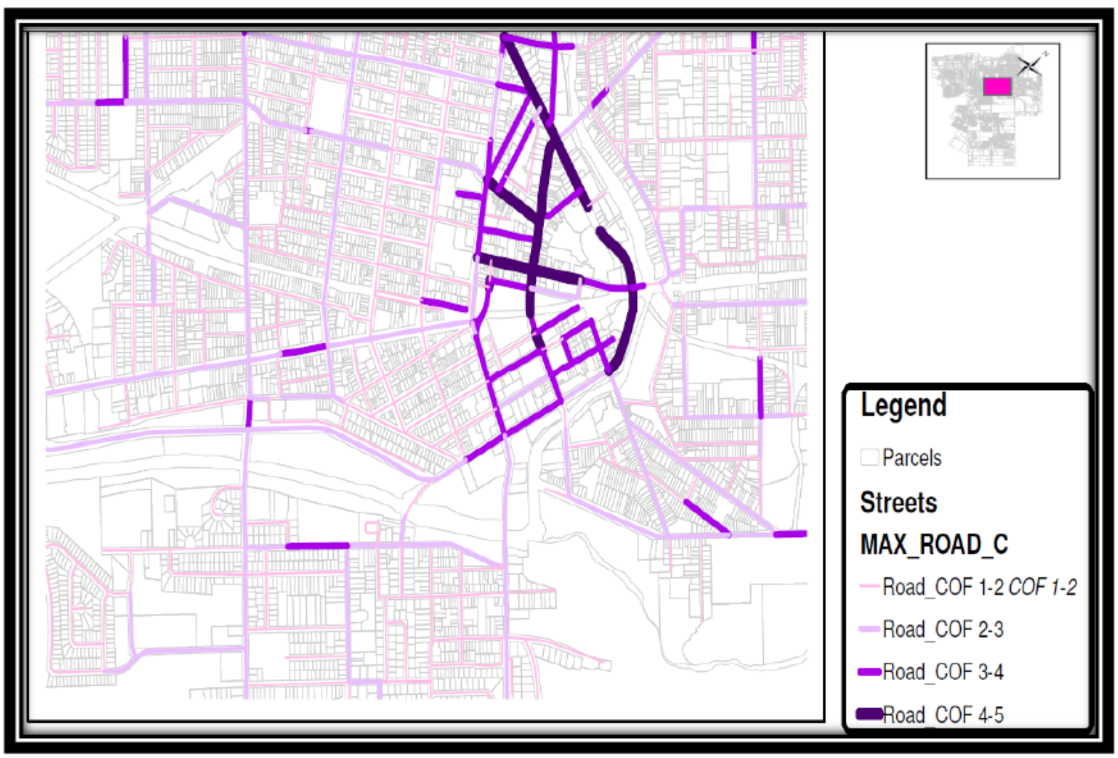


Figure 6-9 City of Guelph Integrated Risk Index Results for Road Segments

The main objective of this Module is to develop a Geographical Information System (GIS) based Risk Model that can be used in day-to-day decision making and capital improvement program prioritization for infrastructure. Identifying which Asset (road, water or sewer) will have the greatest impact on the city will help to optimize maintenance activities and to replace and rehabilitate the selected assets at opportune times in a cost-effective manner. The classifications of asset according to their criticalities are shown in Table 6-6.

Table 6-6 Consequence of Failure Results

		Consequence of Failure				
		Insignificant	Minor	Moderate	Major	Catastrophic
		1	2	3	4	5
Road Segments	No. of segment.	440	1534	1010	191	33
	Percentage (length)	7.9%	50.6%	31.3%	8.9%	1.4%
Watermains	No. of segment.	1777	763	1458	118	13
	Percentage (length)	40.9%	19.9%	34.6%	4.5%	0.1%
Sewermains	No. of segment.	74	733	3823	1884	130
	Percentage (length)	1.2%	11.0%	55.2%	30.2%	2.4%

Results are summarized based on number of pipe segments and percentage based on length. A small number of segments were considered critical according to overall criticality. Also noting that this risk model was applied to the whole network not only the selected sub network.

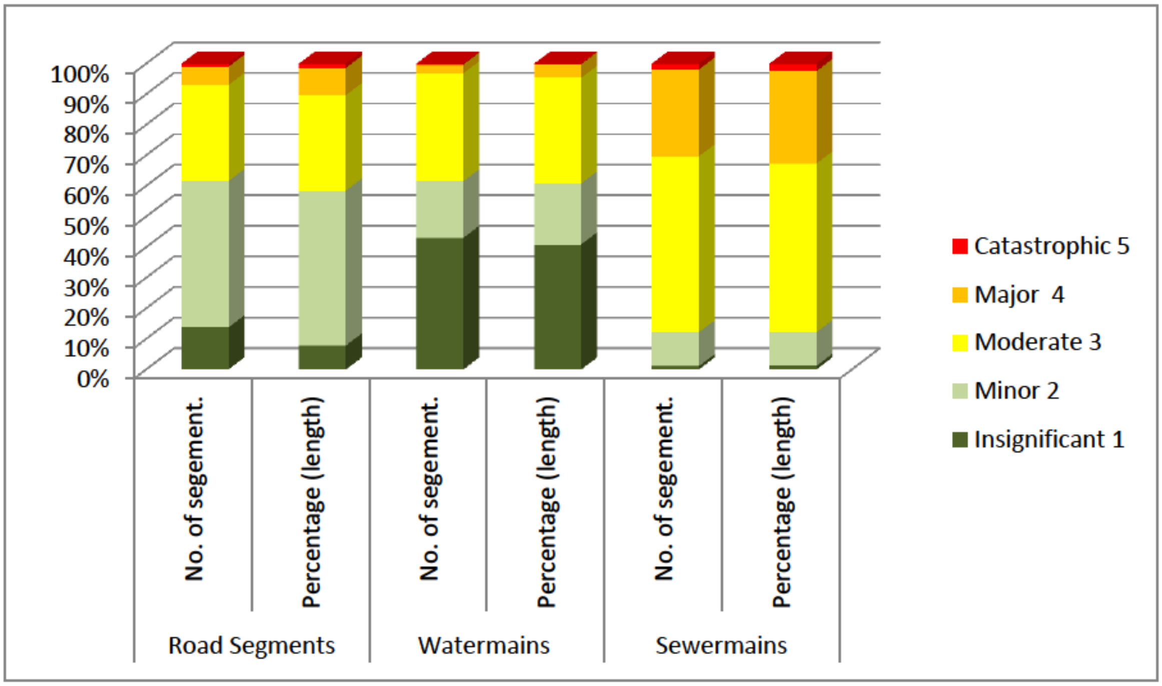


Figure 6-10 Summary of Risk model results

Then the process of calculating the integrated consequence of failure of a combined road, water, and sewer segment is achieved via the integration of the CoF_{Road}, CoF_{Water}, and COF_{Sewer} into one Overall CoF_{All} Index using unsupervised clustering, as discussed in Section 5. Figure 6-11 shows the results of the integrated risk index for the road, water, and sewer network. Data used for clustering include 2382 segment of road, water and sewer asset.

Table 6-7 shows the final cluster centers for each consequence of failure index. Additionally the distributions of these clusters are shown in Table 6-8.

Table 6-7 COF Cluster Centers

	Cluster				
	1	2	3	4	5
Road_COF_Index	1.7019	1.7371	2.4928	2.5408	3.835
Water_COF_Index	1.6152	1.6709	2.2936	2.3099	3.3669
Sewer_COF_Index	2.1032	2.1889	2.7606	3.2878	3.6302

Table 6-8 Summary of Cases in each Cluster

Cluster	Number of Cases in each Cluster
1	592
2	358
3	374
4	955
5	103

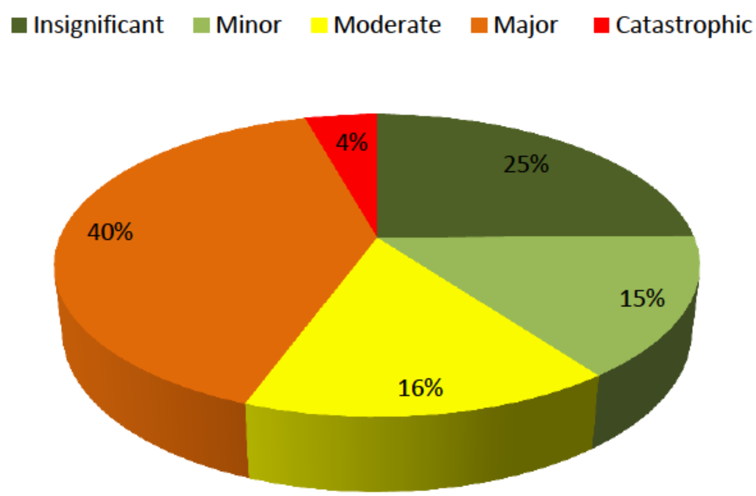


Figure 6-11 Integrated R/W/S Segments Consequence of Failure Clusters

6.1.1 Integrated Risk Model Sensitivity Analysis

A sensitivity analysis was performed to determine which factors have the highest impact on the risk model. A series of What-If scenarios were performed, to measure the impact of changing the main factors and sub factors weights on the integrated risk index results. The sensitivity analysis determines which factors have little impact on risk index outcomes and which are significant.

Figure 6-12 shows a tornado graph that compares the effects of each input risk factors on the overall risk index results. The X-Axis displays the percentage change in risk index value. For each factor (listed on the Y-Axis), a bar is drawn between the extreme values of the risk index as calculated using ±10 percent change in the input values of each factor.

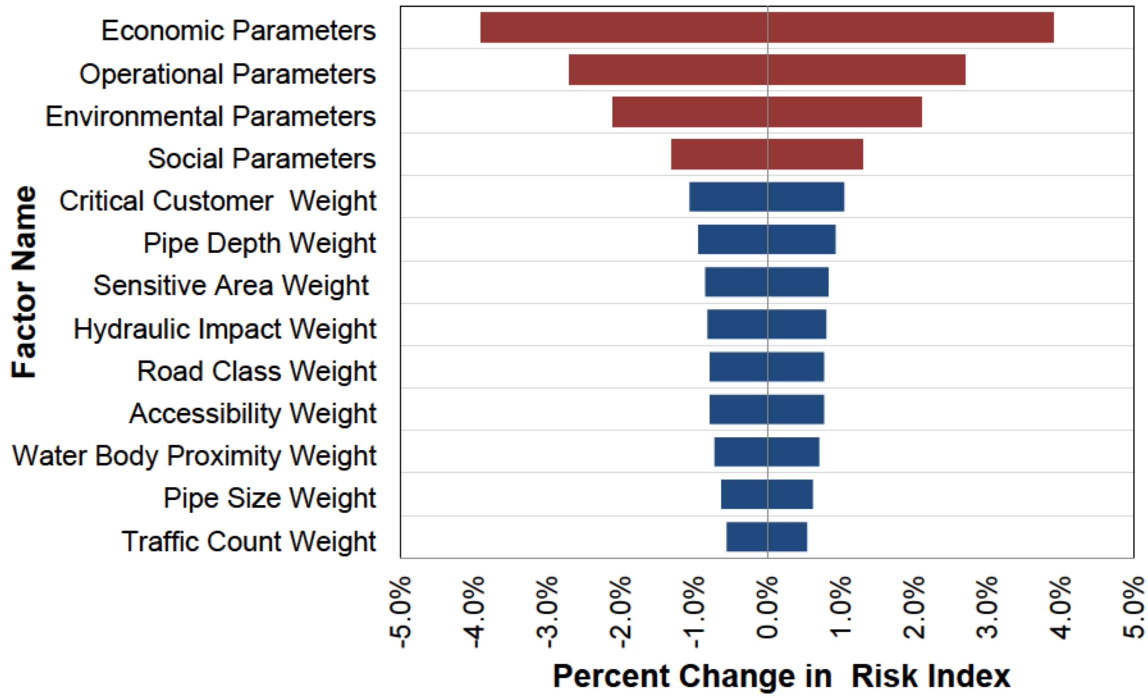


Figure 6-12 Risk Factors Impact on Risk Index

The factor with the greatest range is plotted on the top of the graph, and the other factors proceed down the Y-Axis with decreasing range. The factor that has most influence on the risk index results is Economic, which results in a ±3.9% change in risk index. Followed by operational, environmental, and social factors, which result ±2.7%, ±2.1%, and ±1.3% change in risk index respectively.

Similarly, the input values for the sub factors weights were examined by changing the base input value by ±10%. The sensitivity analysis results showed that percent change in the risk index output were the highest for Critical

Customer (±1.1%), Pipe Depth (±0.9%), and Sensitive Area (±0.8%) factors. Factors that have highest influence on the risk results need more attention, thus a more in depth analysis was performed as shown in Figure 6-13.

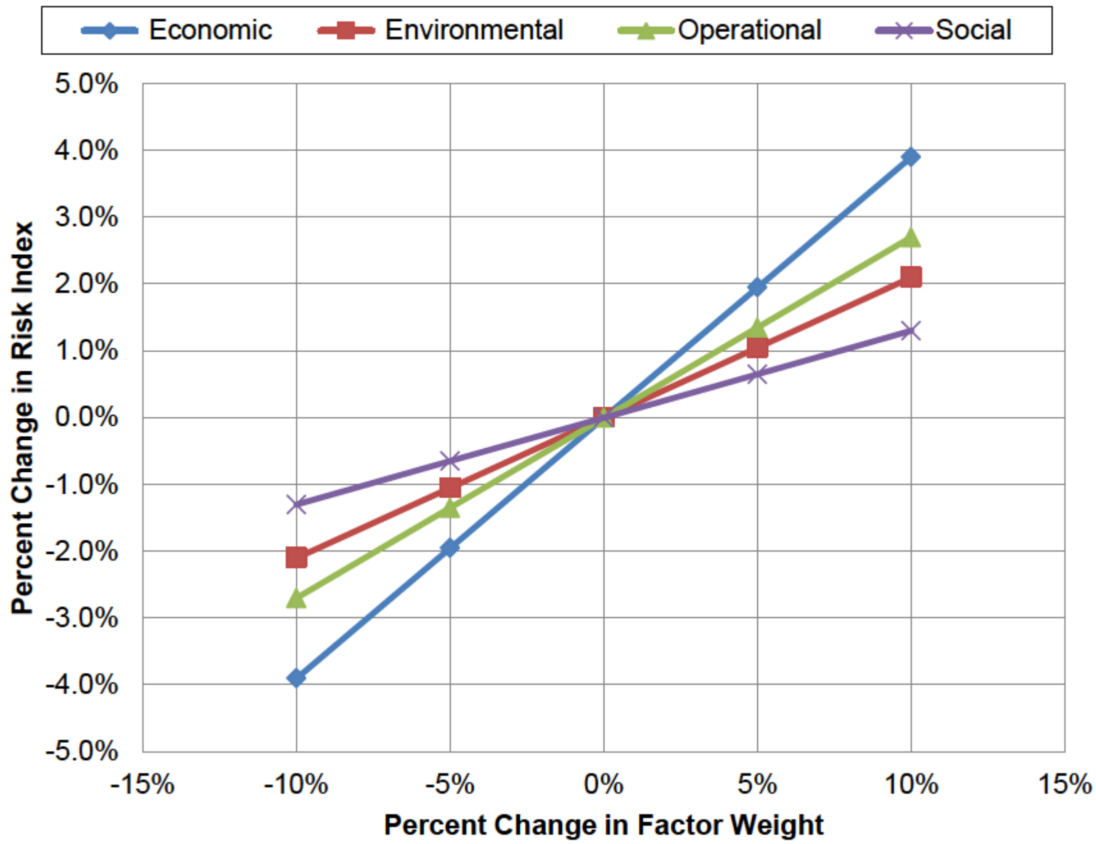


Figure 6-13 Sensitivity Analysis Details of Risk Main Factors

Figure 6-13 shows a graph that compares the risk index results as generated by main risk factors input. For each factor, the percentage of the base case is plotted on the X-Axis and the percent change in risk index value calculated is plotted on the Y-Axis. The slope of each line depicts the relative change in the output per unit change in the input variable. Economic factors have the highest impact on the overall risk index results and it has the steepest slop.

6.1.2 Consequence of Failure Score Sensitivity Analysis

A sensitivity analysis was performed to determine which factors score have the highest impact on the consequence of failure model. A series of What-If scenarios were performed, to measure the impact of changing any factor score on the consequence of failure index results. The sensitivity analysis determines which factors have little impact on consequence of failure index outcomes and which are significant. Five different consequence of failure ranges (i.e. COF index 1 to 5) were selected to perform a detailed sensitivity analysis on them.

Figure 6-14 shows a tornado graph that compares the effects of COF score on the COF index results. The input values for the COF factors Score were examined by changing the base input value of 3 by ±66.7% (i.e. Score values examined are 1,2,3,4 and 5). The sensitivity analysis results showed that percent change in the COF index output were the highest for Pipe Size ((±7.04%), Critical Customer (±7.02%), Traffic Count (±6.32%) and Pipe Depth (±6.24%) factors score.

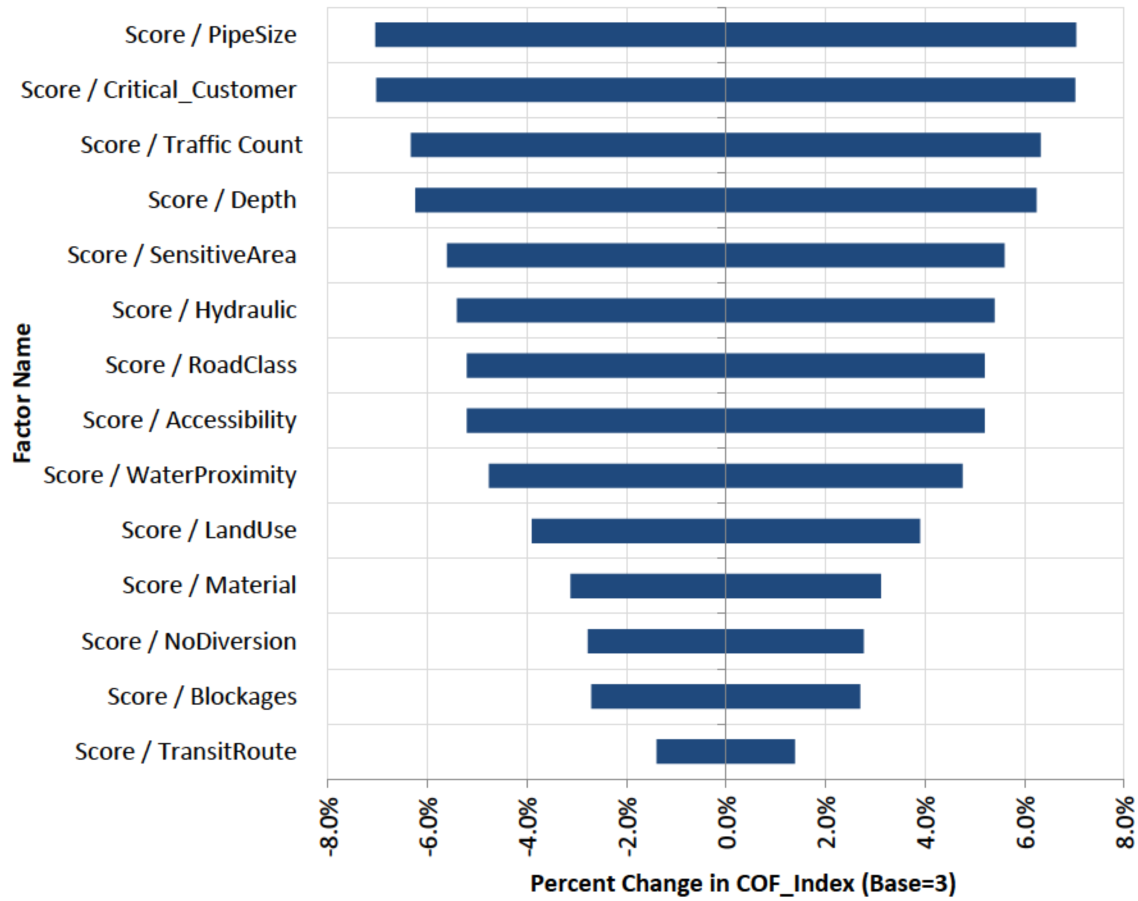


Figure 6-14 COF Factors Score Impact on COF Index

Table 6-9 compares the COF index results as generated by COF factors scores input. For each factor Score, the value of COF score as shown in the first two columns, the value and percent change in COF index calculated is for five different cases of COF index. Such that "COF_Index/1", "COF_Index/2", "COF_Index/3", "COF_Index/4", and "COF_Index/5" represents a base value for COF of 1,2,3,4, and 5. The COF index output values were calculated by changing the score of the candidate factor (e.g. pipe size, critical customer, etc.) from their base value within a range of 1 to 5. The highest impact was for "pipe size" followed by "critical customer" with a 42% increase in the overall COF index from the base value of 1.0. While this might seem high impact, it should be noted that while COF index changed from 1.0 to 1.42 it remained within the Insignificant (Green) Consequence Level zone. Thus there is a high impact on the risk index by changing one factor score, but this impact insignificantly changed the COF index zone .

Table 6-9 Sensitivity Analysis Details of COF Score

	Input Variation	Output Variation									
		COF_Index / 1		COF_Index / 2		COF_Index / 3		COF_Index / 4		COF_Index / 5	
Factor Name	**Score Value**	**Value**	**Change (%)**	**Value**	**Change (%)**	**Value**	**Change (%)**	**Value**	**Change (%)**	**Value**	**Change (%)**
Score / Pipe Size	1	1.00	0.00%	1.89	-5.28%	2.79	-7.04%	3.68	-7.92%	4.58	-8.45%
	2	1.11	10.56%	2.00	0.00%	2.89	-3.52%	3.79	-5.28%	4.68	-6.34%
	3	1.21	21.12%	2.11	5.28%	3.00	0.00%	3.89	-2.64%	4.79	-4.22%
	4	1.32	31.68%	2.21	10.56%	3.11	3.52%	4.00	0.00%	4.89	-2.11%
	5	1.42	42.24%	2.32	15.84%	3.21	7.04%	4.11	2.64%	5.00	0.00%
Score / Critical Customer	1	1.00	0.00%	1.89	-5.27%	2.79	-7.02%	3.68	-7.90%	4.58	-8.42%
	2	1.11	10.53%	2.00	0.00%	2.89	-3.51%	3.79	-5.27%	4.68	-6.32%
	3	1.21	21.06%	2.11	5.26%	3.00	0.00%	3.89	-2.63%	4.79	-4.21%
	4	1.32	31.59%	2.21	10.53%	3.11	3.51%	4.00	0.00%	4.89	-2.11%
	5	1.42	42.12%	2.32	15.80%	3.21	7.02%	4.11	2.63%	5.00	0.00%
Score / Traffic Count	1	1.00	0.00%	1.91	-4.75%	2.81	-6.33%	3.72	-7.12%	4.62	-7.59%
	2	1.09	9.49%	2.00	0.00%	2.91	-3.16%	3.81	-4.75%	4.72	-5.69%
	3	1.19	18.98%	2.09	4.75%	3.00	0.00%	3.91	-2.37%	4.81	-3.80%
	4	1.28	28.47%	2.19	9.49%	3.09	3.16%	4.00	0.00%	4.91	-1.90%
	5	1.38	37.96%	2.28	14.24%	3.19	6.33%	4.09	2.37%	5.00	0.00%
Score / Depth	1	1.00	0.00%	1.91	-4.68%	2.81	-6.24%	3.72	-7.02%	4.63	-7.49%
	2	1.09	9.36%	2.00	0.00%	2.91	-3.12%	3.81	-4.68%	4.72	-5.62%
	3	1.19	18.72%	2.09	4.68%	3.00	0.00%	3.91	-2.34%	4.81	-3.74%
	4	1.28	28.08%	2.19	9.36%	3.09	3.12%	4.00	0.00%	4.91	-1.87%
	5	1.37	37.44%	2.28	14.04%	3.19	6.24%	4.09	2.34%	5.00	0.00%

6.2 Performance Assessment- CDPM Results

The developed Client driven performance measure module provides a structured framework to apply a consistent LOS approach to road, water, and sewer assets.

A CDPM map was developed using the data collected from the case study. The tool runs on a GIS platform to visualize the areas with performance concerns to prioritize O&M and capital construction funding.

Each CDPM parameter has various variables / attributes in which they are not similar in their effect on customer stratification. Most assets within the city were in good to very good performance from a customer perspective, a total of 550 segments were analyzed.

Table 6-10 summarizes the CDPM factors, ranges and data processing approach for watermains. The CDPM model calculated the minimum, expected and maximum CDPM value for those assets using the previously developed fuzzy membership functions for each factor. Watermain CDPM factors include Water Quality Complaints, Water Pressure Complaints, Water Segment Interruption (Breaks), and Duration of Interruption (Accessibility). Most of the input values for watermains CDPM model were in the very good to good performance range.

Table 6-10 Watermain CDPM Factors and Data Processing Approach

Factor	Range (sub-network)	Data processing notes
Water Quality Complaints	• Range : 0 to 1 • Only six segments had a water quality compliant	Call center data was utilized to spatially allocate the number of water quality complaints to various zones of the city. The number of complaints was then allocated to each watermain segment within this zone using GIS spatial analysis.
Water Pressure Complaints	• Range : 0 to 1 • Range : 0 to 1 • Only five segments had a water quality compliant	Call center data was utilized to spatially allocate the number of Water Pressure Complaints to various zones of the city. The number of complaints was then allocated to each watermain segment within this zone using GIS spatial analysis.
Water Segment Interruption (Breaks)	• Range : 0 to 10 • Fifty (50) segments had a watermain breaks	A shape file containing break data has been provided by the City as well as breaks that have not been mapped. The breaks that have not been mapped did not specify the pipe the break occurred on (therefore were not used in this analysis) ; the breaks were attributed to mains using a GIS spatial analysis.
Duration of Interruption (Accessibility)	• All segments had good accessibility	A list of pipes with marginal and low accessibility was obtained from the City.

Once data was prepared, it is then entered into the CDPM module to calculate the fuzzy membership function for each network model as discussed in chapter 5. Figure 6-15, shows the CDPM results for watermains assets. As shown in the figure below, results have an average expected CDPM index of 3 which represents a good customer satisfaction on the CDPM scale.

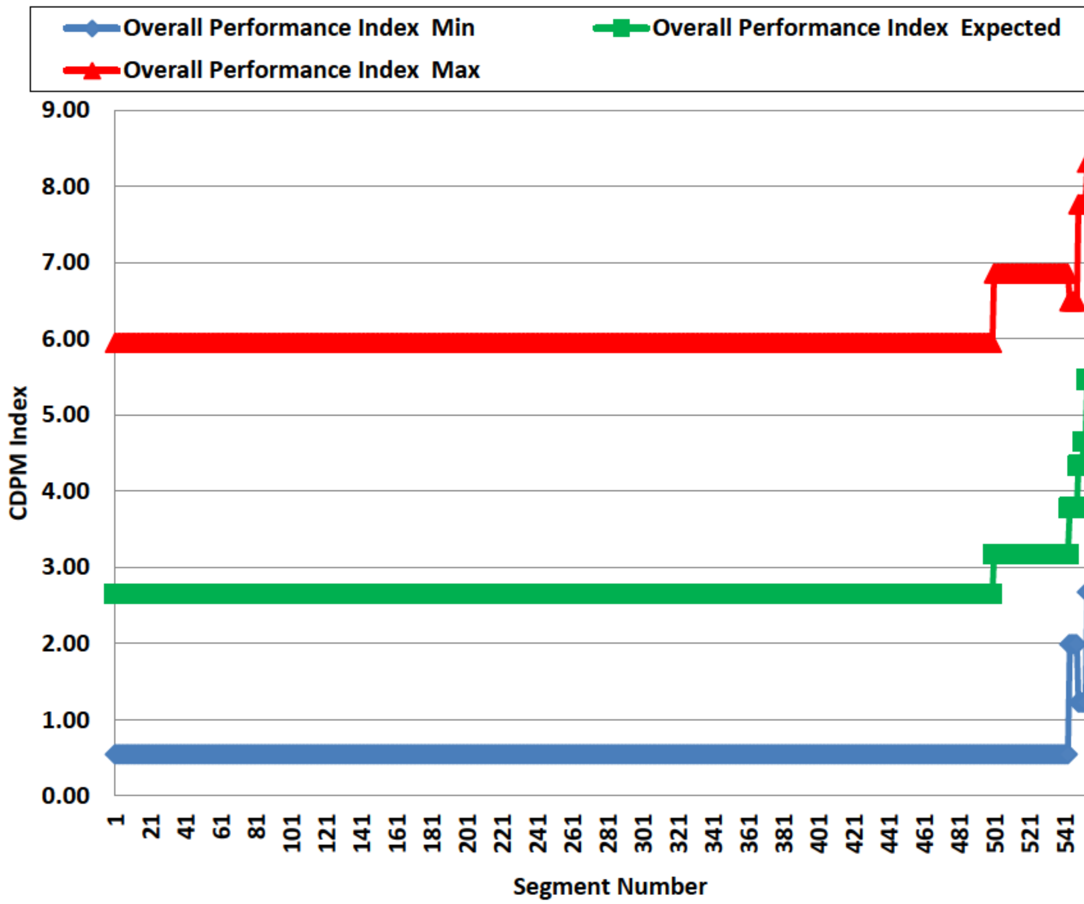


Figure 6-15 Water CDPM Results

Similarly, Table 6-11 shows the CDPM factors and data processing approach for roads. This model included two CDPM factors (Road Roughness and Annual number of crack seal/ segment). These two factors were directly imported from the city's pavement management system. The input values for both these factors were diverse and represented a distinct performance range.

Table 6-11 Road Segments CDPM Factors and Data Processing Approach

Factor	Range (sub-network)	Data processing notes
Road Roughness	• Range: 2 to 9	The data type to be used for this performance measure factor is RCI index. Data was obtained from the city's pavement management system (road matrix)
Annual number of crack seal/ segment	• Range: 0 to 1 • Eleven (11) segment segments had crack seal	The data type to be used for this performance measure factor is annual number of crack seal/ segment. Data was obtained from the city's pavement management system (road matrix)

The data is then entered into the CDPM module to calculate the fuzzy membership function for each network. Figure 6-16 shows the CDPM results for road assets. As shown in the Figure 6-16, results have an average expected CDPM index of 4.1 which represents a fair customer satisfaction on the CDPM scale. Due to the diversity in the input values, the CDPM results were stretched out across the CPDM scale from excellent to poor performance.

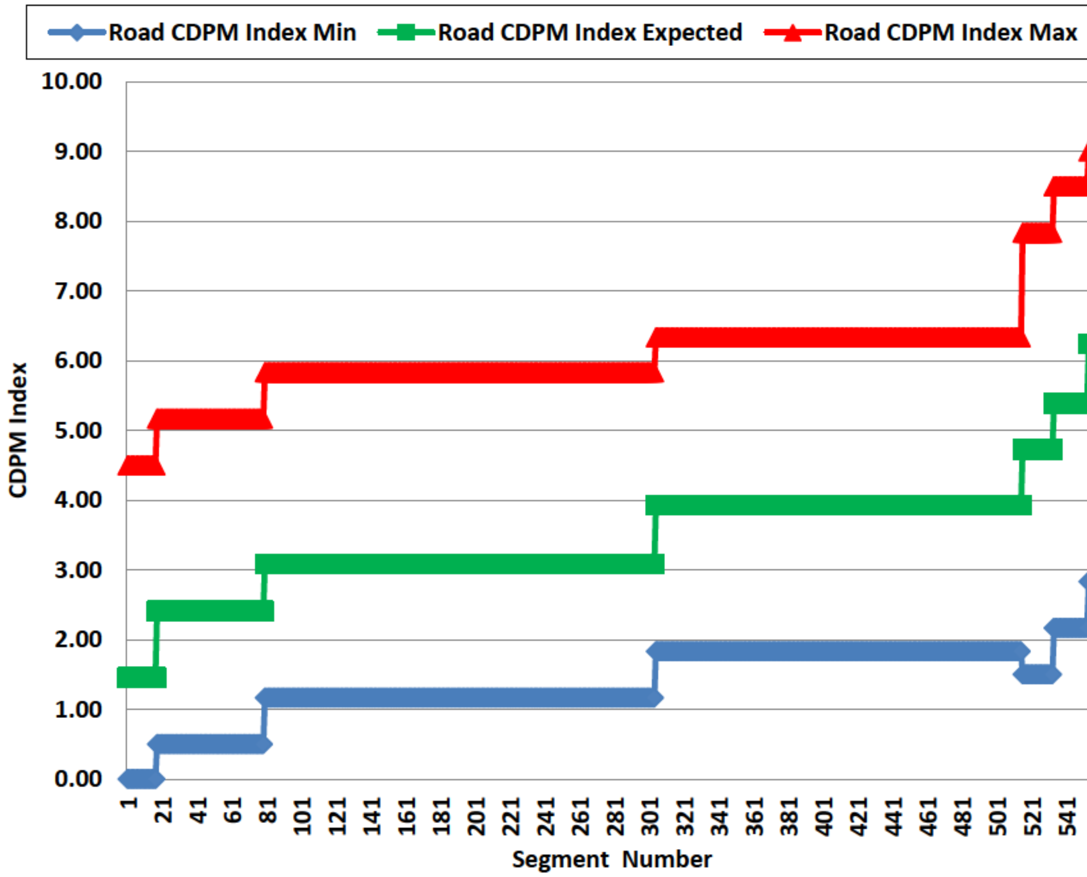


Figure 6-16 Roads CDPM Results

Similarly Table 6-12 shows the CDPM factors and data processing approach for sewermains. Sewermain CDPM factors include: Number of sewermain blockage / useful life, Annual no. of sewermain backups/ segment, and Capacity issues. Most of the input values for sewermains CDPM model were in the very good to excellent performance range, which should results in a very good/ excellent customer stratification results.

Figure 6-17, show the CDPM results for sewermains assets. As shown in the figure below, results has an average expected CDPM index of 2 which represents a very good customer satisfaction on the CDPM scale.

Table 6-12 Sewermain CDPM Factors and Data Processing Approach

Factor	Range (sub-network)	Data processing notes
Number of sewermain blockage / useful life	None	CCTV inspection videos were provided by the city. Analysis of the sewermain blockage based on WRC codes was conducted. A list of sewermains with blockage history was then compiled.
Annual no. of sewermain backups/ segment	None	Data was obtained from the City, a list of sewermains with backup's history.
Capacity issues	• Range(d/D) : 0.01 to 0.6	The data type to be used for this performance measure factor is peak value of depth of flow divided by the pipe diameter (d/D). Data was obtained from the sewer hydraulic model.

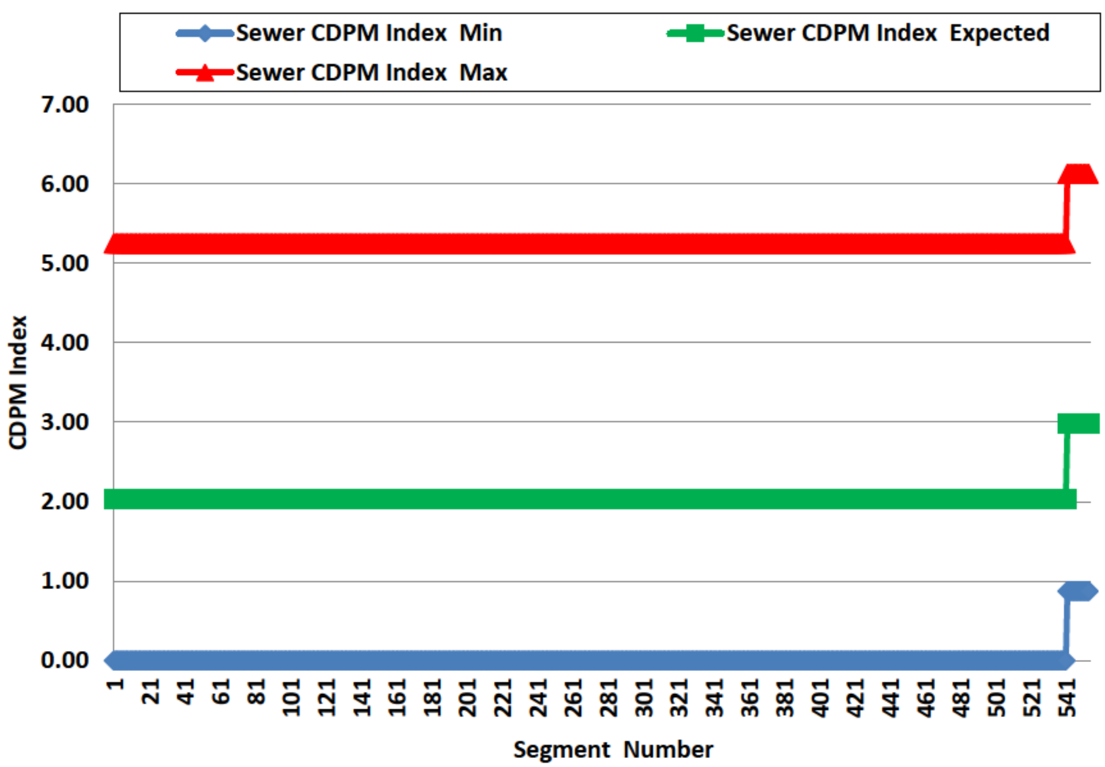


Figure 6-17 Sewer CDPM Results

Once the CDPM index values were calculated for road, water and sewer assets separately, the results are then integrated into on overall CDPM index using weighted average. Table 6-13 shows the overall weights for each factor and its contribution to the overall CPDM index weight. It should be noted that CDPM workshop participants agreed that each model (road, water and sewer) should have an equal contribution to the overall integrated CDPM index. Therefore each model (road, water and sewer) was assigned a weight of 0.333.

Table 6-13 CDPM Factor Weights

Performance Measure	Factor Weight	Overall weight
Roads = 0.34		
Roughness Rating (RPI)	0.60	0.20
# crack seal/ segment	0.40	0.13
Water: 0.33		
# Water quality complaints	0.10	0.03
# Water Pressure complaints	0.26	0.09
# Segment interruption (breaks)	0.45	0.15
Average duration of interruption (Accessibility)	0.18	0.06
Sewer: 0.33		
Sewermains Capacity issues	0.50	0.17
Number of Sewermains Main Blockages	0.25	0.08
Annual Number of Sewermains Main Backups/ Segment	0.25	0.08

The model calculated the minimum, expected and maximum value for those assets as shown in Figure 6-18 and results matched the expectation of the city staff. The expected overall CDPM index ranges from 2 to 4, which represents a good customer satisfaction on the CDPM scale.

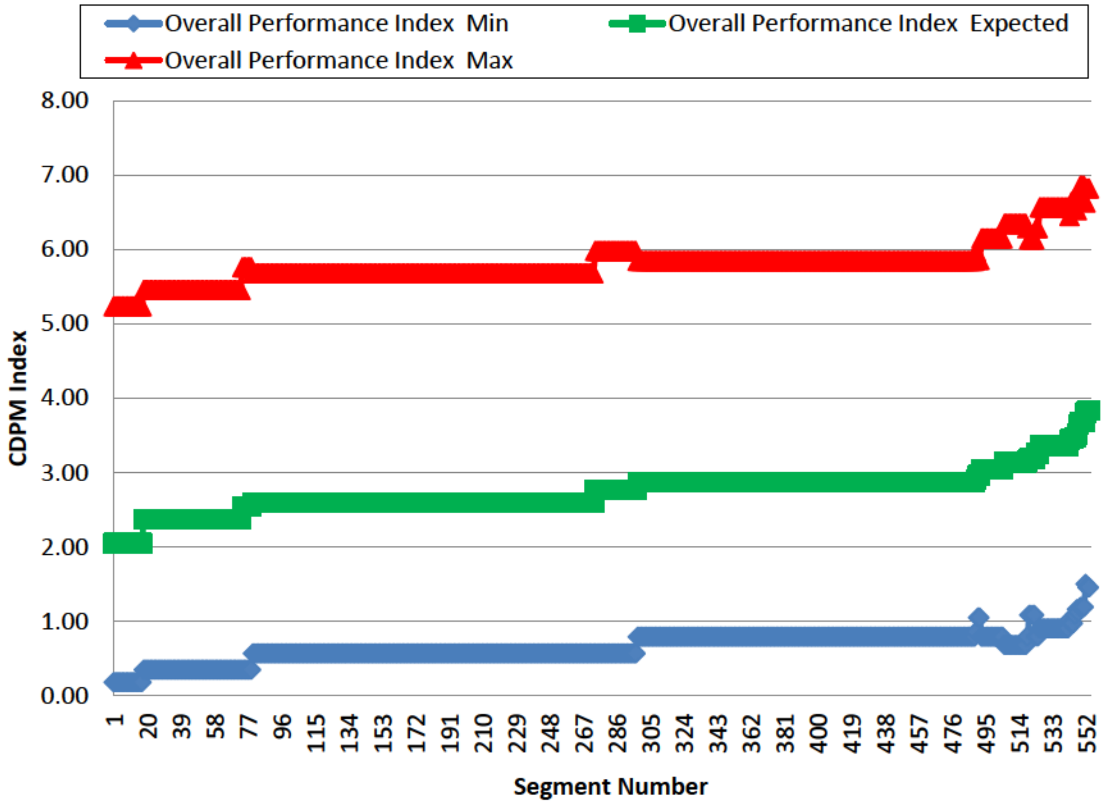


Figure 6-18 Overall CDPM Index Results for Sample Selected Assets

Figure 6-19 shows the expected CDPM index values for road, water and sewer segment versus the integrated combined Expected CDPM index. The road CDPM index results are the highest with a diverse range from 1.5 to 6.5, Water CDPM index ranges 2.5 to 5.5, while sewer CDPM index is the lowest with a CDPM index ranging from 2 to 3. The model calculated the expected CDPM value for each asset then assigned an overall CDPM index for the overall integrated assets. As shown in Figure 6-19 the overall CDPM index has normalized the results and assigned an average score based on the road, water and sewer weights. The expected overall CDPM index ranges from 2 to 4, which represents a good customer satisfaction on the CDPM scale.

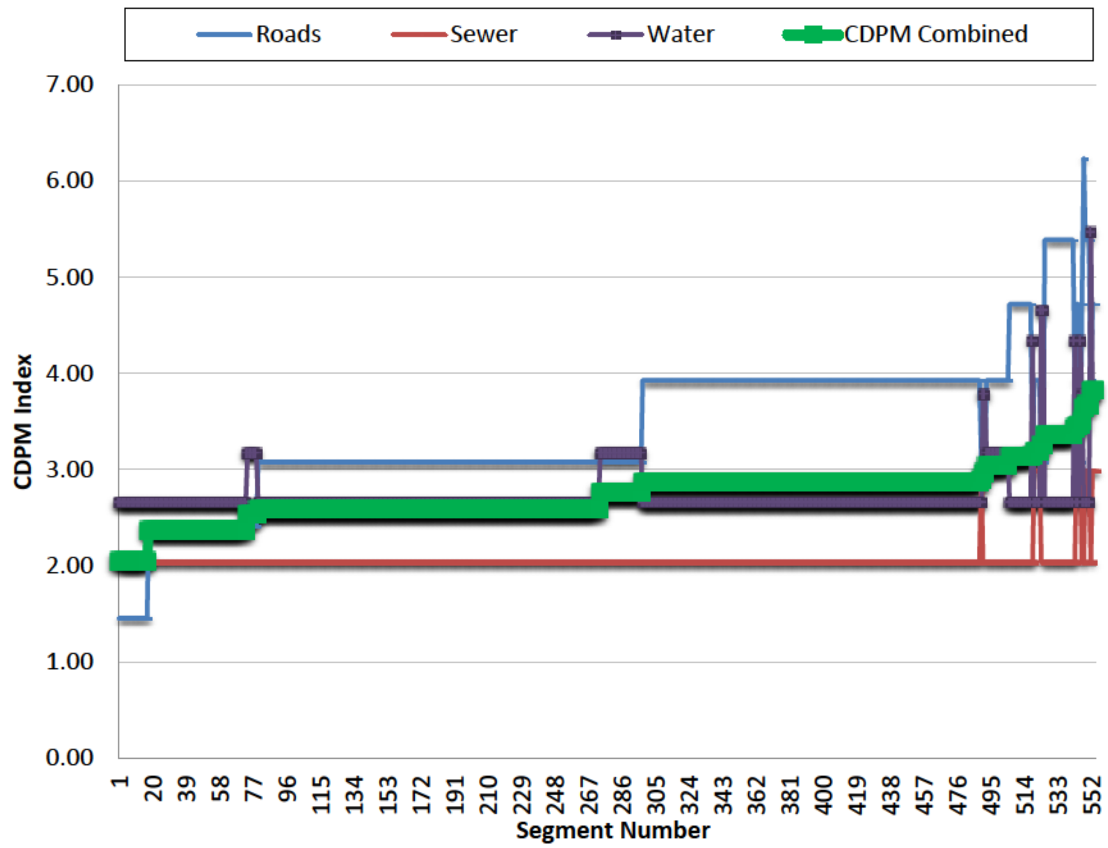


Figure 6-19 Overall CDPM Index Expected Values

6.2.1 CDPM Model Sensitivity Analysis

A sensitivity analysis was performed to determine which factors have the highest impact on the CDPM model. A series of What-If scenarios were performed, to measure the impact of changing the main factors and sub factors weights on the integrated CDPM index results. The sensitivity analysis determines which factors have little impact on CDPM index outcomes and which are significant.

Figure 6-20 shows a tornado graph that compares the effects of all input CDPM performance factors on CDPM index results. The X-Axis displays the percentage change in CDPM index value. For each factor (listed on the Y-Axis), a bar is drawn between the extreme values of the CDPM index as calculated using ±10 percent change in the input values of each performance factor.

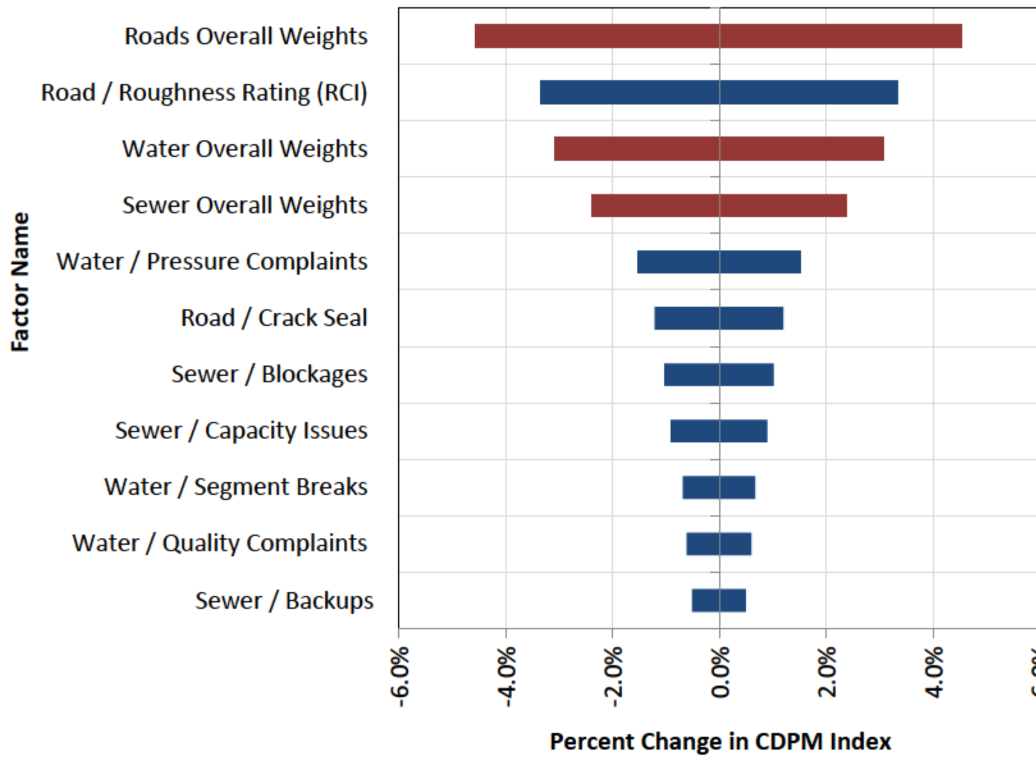


Figure 6-20 CDPM Factors Impact on CDPM Index

The factor with the greatest range is plotted on the top of the graph, and the other factors proceed down the Y-Axis with decreasing range. The factor that has most influence on the CDPM index results is road overall weight, which results in a ±4.6% change in CDPM index. Followed by water and sewer factors overall weight, which result ±3.1% and ±2.4% change in CDPM index respectively. Similarly, the sensitivity analysis results for sub factors weights showed that percent change in the CDPM index output were the highest for Road Roughness Rating (±3.4%), Water / Pressure Complaints (±1.5%), Road / Crack Seal (±1.2%), and Sewer / Blockages (±1.0%) factors.

Figure 6-20 shows a graph that compares the CDPM index results as generated by major CDPM performance factors input. For each factor, the percentage of the base case is plotted on the X-Axis and the percent change in CDPM index value calculated is plotted on the Y-Axis. The slope of each line depicts the relative change in the output per unit change in the input variable. Road Roughness Rating has the highest impact on the overall CDPM index results and it has the steepest slope.

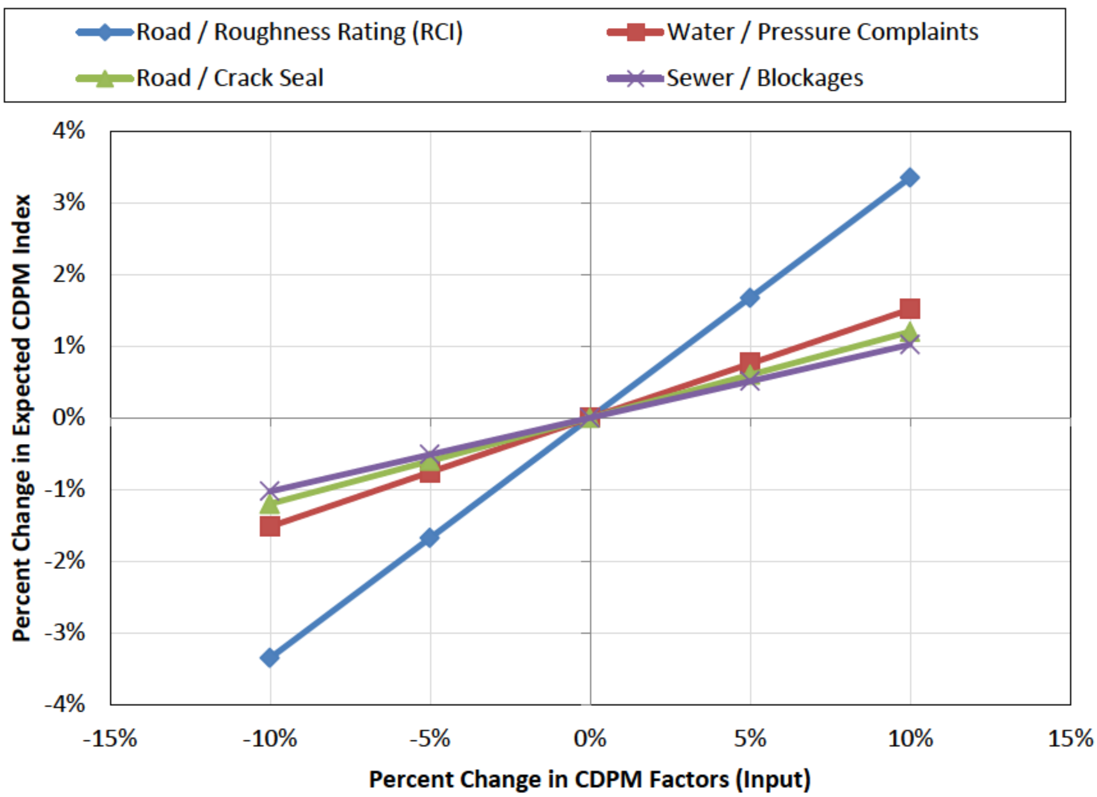


Figure 6-21 Sensitivity Analysis Details of CDPM Major Performance Factors

6.3 Investment Planning- ODM Results & Analysis

The analysis was conducted for a portion of the city of Guelph network. The results are presented in Table 6-18. A total of 514 projects over the next 20 years were evaluated. The objective is to maximize the risk reduced per NPV dollars spent under condition and CDPM constraints with unlimited budget. As illustrated in Table 6-18 most of the projects were recommended in year one as there was no limit to the budget.

The variables and constraints required for this model are listed in Table 6-14. The most important part is that the decision variables must be binary, where a 1 means an investment is chosen and 0 means it is not.

Table 6-14 ODM Unlimited Budget - Variables and Constraints

Variable / Constraints	Descriptions
Input Variables	• Initial cash required for investment, • Spatially linked assets • Proposed life cycle profile • Consequence of failure and probability of failure for each segment • Current Condition and Age • CDPM index
Decision variables (changing cells)	• Whether to invest (binary variables)
Objectives (target cell)	• Total risk reduced per dollar spent
Other calculated variables	• NPV from investment • Probability of failure at intervention • Future condition at intervention • Total initial cash required
Constraints	• Average network Condition after intervention should be greater than or equal minimum Condition (i.e. Road network greater than 50 PCI, water network less than 3, sewer network less than 3) • Average network CDPM index should be greater than or equal minimum CDPM (i.e. CDPM less than or equal 4)

The user defines the values for the cost data of the selected Asset class or category as indicated in Table 6-15, Table 6-16, and Table 6-17 below. The user can select or edit more than one parameter to collect the life cycle cost for them. In this example, watermains and sewermains costs based on diameter and roads costs based on surface area were selected. All cost data units should be entered in \$/m for (water and sewer) and \$/m^2 for roads.

Table 6-15 Cost Assumptions for Sanitary Sewers

Diameter > =	Diameter <	Replacement Cost / m	Trenchless Cost /m	O&M Cost /m
0	200	**\$350**	**\$300**	**\$4**
200	300	**\$500**	**\$450**	**\$4**
300	500	**\$800**	**\$700**	**\$5**
500	700	**\$1,200**	**\$1,000**	**\$5**
700	1000	**\$1,700**	**\$2,000**	**\$10**
1000	1200	**\$2,200**	**NA**	**\$10**

Table 6-16 Cost Assumptions for Watermains

Diameter > =	Diameter <	Replacement Cost / m	Trenchless Cost/m	O&M Cost/m
0	100	**\$100**	**\$200**	**\$4**
100	150	**\$200**	**\$200**	**\$4**
150	200	**\$250**	**\$300**	**\$4**
200	300	**\$500**	**\$400**	**\$4**
300	400	**\$700**	**\$550**	**\$5**
400	800	**\$1,200**	**\$700**	**\$7**
800	1000	**\$1,400**	**\$1000**	**\$7**
1000	1200	**\$1,800**	**NA**	**\$10**

Table 6-17 Cost Assumptions for Road

Intervention Actions	Cost per square meter
O&M (Crack Seal & patching)	\$5.00
Full Mat Replacement - Arterial	\$49.00
Full Mat Replacement - Collector	\$45.00
Full Mat Replacement - Local	\$37.50
Rehab. (Shave / Overlay)	\$25.00

Table 6-18 Optimization Results for Sub Network of the City Assets

Investment Year	Risk/ NPV $ Spent Index	Project Costs	Number of projects						
			S1- Road	S2- Sewer	S3- Water	S4- Water/ Road	S5- Sewer/Road	S6- Water/Sewer/Road	S7- Water/Sewer(trenchless)
1	994.1	$50,029,848	19	12	2	100	64	146	6
2	18.3	$1,372,546	0	0	0	1	0	6	0
3	19.0	$1,079,863	0	0	0	3	0	4	0
5	62.3	$2,852,800	0	0	0	9	2	14	0
6	12.0	$362,337	0	1	0	2	1	0	0
7	27.7	$1,394,101	1	0	0	7	1	3	0
8	44.8	$3,868,448	1	0	0	4	2	8	0
11	28.2	$1,049,387	0	4	0	0	2	2	0
12	36.6	$1,301,531	0	0	0	0	13	0	0
13	14.2	$490,659	0	1	0	0	3	1	0
14	20.2	$483,715	0	3	0	0	5	0	0
15	9.1	$252,274	0	0	1	0	3	0	0
16	10.4	$144,666	0	0	0	1	2	0	0
17	5.3	$342,545	0	0	0	0	2	0	0
18	15.8	$274,416	0	0	0	0	6	0	0
19	36.2	$1,128,017	1	0	0	1	10	0	0
20	11.2	$35,937	0	0	0	0	3	0	0
Grand Total	**1365.1**	**$66,463,091**	**22**	**21**	**3**	**128**	**119**	**184**	**6**

As also presented in Figure 6-22 the largest portion of projects, over 84%, were recommend under integration option (road /water/ sewer 36%, Road/sewer 23%, Road/water 25%) as it yields the maximum gains for the invested money.

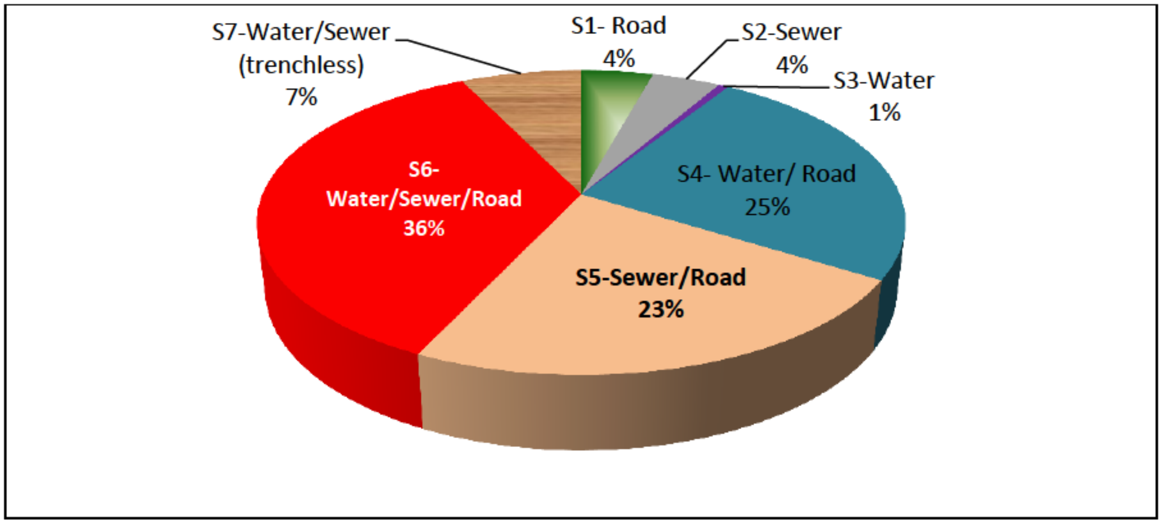


Figure 6-22 Percentage Distribution of Intervention Option Results

Further analysis was conducted to compare the average condition and CDPM index constraints with the total number of projects recommended under the integrated option as shown in Table 6-19.

Table 6-19 Results for Integrated Projects & Constraints

Year	Sum of Risk Reduced per $ Spent	Sum of Project cost	Average of Road Initial Condition	Average of Sewer Initial Condition	Average of Water Initial Condition	Sum of S6-Water/Sewer/Road
1	410.4	$31,796,448	42.7	3.9	4.9	146
2	15.8	$1,354,871	43.0	4.6	4.7	6
3	10.5	$847,457	64.3	4.6	4.9	4
5	31.4	$2,507,165	33.0	4.5	4.8	14
7	8.1	$721,145	55.3	4.8	4.9	3
8	25.5	$2,233,711	18.4	4.9	5.0	8
11	6.9	$654,777	14.9	5.0	3.4	2
13	3.0	$211,298	28.9	5.0	3.2	1
Total	511.6	$40,326,872	41.25	4.07	4.81	184

Table 6-20 below highlights the average and variance risk reduced per dollar spent in investment for each intervention option.

Table 6-20 Stats for Risk Reduced per Dollar Spent

Intervention option	Number of Projects	Average of Risk/ $ spent (NPV)	Variance of Risk/ $ spent (NPV)
S1- Road	22	1.57	0.96
S2-Sewer	21	2.01	0.66
S3-Water	3	2.18	0.85
S4- Water/ Road	128	2.94	0.50
S5-Sewer/Road	119	2.96	0.62
S6-Water/Sewer/Road	184	2.78	0.46
S7-Water/Sewer(trenchless)	37	3.74	0.10
Grand Total	**514**	**2.78**	**0.68**

Figure 6-23 shows a GIS map illustrating the results of a sub network under unlimited budget constraints, where this section was identified as the highest consequence of failure with a poor condition for most of their infrastructure. Currently, the condition constraints is capped at a minimum of poor condition (Road at 65, water at 3, sewer at 3) adjustment of these constraints can be made to relax it and reduce the total number of projects to be recommended for intervention.

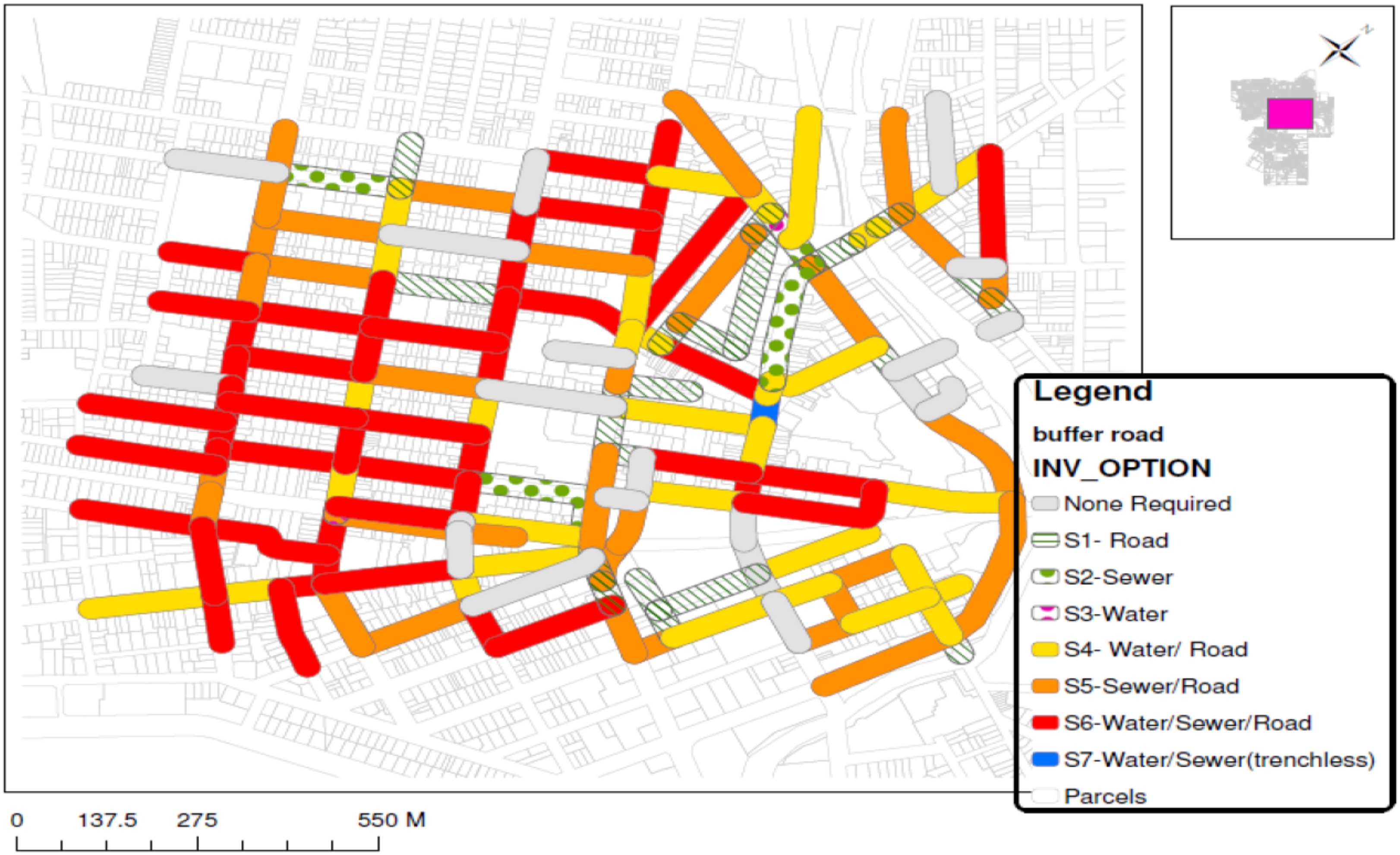


Figure 6-23 ODM Results Under Unlimited Budget Constraints

A further analysis was done for this sub network with limited budget constraints. Twenty seven (27) projects were further analyzed as shown below. The variables and constraints required for this model are listed in Table 6-21. The most important part is that the decision variables must be binary, where a 1 means an investment is chosen and 0 means it is not.

Table 6-21 Variables and Constraints for the ODM Limited Budget

Variable / Constraints	Descriptions
Input Variables	• Initial Cash required for investment, • Budget for road , water and sewer • Spatially linked assets • Proposed life cycle profile • Consequence of failure and probability of failure for each segment • Current Condition and Age • CDPM index
Decision variables (changing cells)	• Whether to invest (binary variables)
Objectives (target cell)	• Total risk reduced per dollar spent
Other calculated variables	• NPV from Investment • Probability of failure at intervention • Future condition at intervention • Total initial cash required
Constraints	• Total initial cash required must be less than or equal to budget. • Future Condition at Intervention should be poor or worse (i.e. Road less than 65 PCI, water greater than 3, sewer greater than 3) • Average Network Condition after intervention should be greater than or equal min Condition (i.e. Road network greater than 50 PCI, water network less than 3, sewer network less than 3) • Average Network CDPM index should be greater than or equal min CDPM (i.e. CDPM less than or equal 4)

Table 6-22 Input Data under Limited Budget Constraints

Project ID	ID			Condition			COF			Capital Project Cost (Replacement)		
	Road Segment ID	Sewer Asset_ID	Water OID	Road	Sewer	Water	Road	Sewer	Water	Road	Sewer	Water
31	6705	PWOPRSED0002767	WLNE101674	42.81	4.25	5.00	1.72	2.56	1.44	$ 279,679	$ 28,300	$ 39,232
34	5547	PWOPRSED0001379	WLNE103490	42.51	4.54	5.00	2.92	2.76	1.54	$ 217,064	$ 46,200	$24,820
35	5543	PWOPRSED0001377	WLNE103705	27.66	4.54	5.00	3.10	3.08	1.60	$ 198,188	$ 43,500	$ 20,380
42	6680	PWOPRSED0001887	WLNE103527	30.36	4.46	5.00	1.96	2.96	1.56	$ 68,623	$ 22,750	$ 1,930
66	6462	PWOPRSED0001415	WLNE102471	60.7	4.54	5.00	3.40	3.86	2.80	$ 467,177	$ 45,700	$63,355
67	6462	PWOPRSED0001416	WLNE102471	60.7	4.54	5.00	3.40	2.80	2.80	$ 467,177	$ 46,100	$ 63,355
68	6462	PWOPRSED0001417	WLNE102471	60.7	4.54	5.00	3.40	3.65	2.80	$ 467,177	$ 46,150	$ 63,355
69	6462	PWOPRSED0001418	WLNE102471	60.7	4.54	5.00	3.40	3.08	2.80	$ 467,177	$ 11,150	$ 63,355
74	6462	PWOPRSED0001415	WLNE102651	60.7	4.54	5.00	3.40	3.86	3.20	$ 467,177	$ 45,700	$ 15,928
75	6462	PWOPRSED0001416	WLNE102651	60.7	4.54	5.00	3.40	2.80	3.20	$ 467,177	$ 46,100	$ 15,928
546	5546		WLNE103733	14.24	0.00	5.00	2.92	0.00	1.54	$ 103,813	$ -	$ 2,680
320	5544		WLNE103734	15	0.00	5.00	2.44	0.00	1.54	$ 37,797	$ -	$ 2,680
76	6462	PWOPRSED0001417	WLNE102651	60.7	4.54	5.00	3.40	3.65	3.20	$ 467,177	$ 46,150	$15,928
77	6462	PWOPRSED0001418	WLNE102651	60.7	4.54	5.00	3.40	3.08	3.20	$ 467,177	$ 11,150	$15,928
137	6448	PWOPRSED0001255	WLNE103531	31.1	4.54	5.00	2.80	3.24	1.54	$ 105,952	$ 43,300	$ 41,750
140	6703	PWOPRSED0002778	WLNE102308	40.79	4.50	5.00	1.60	2.80	1.44	$ 148,262	$ 34,900	$ 42,605
147	6568	PWOPRSED0001909	WLNE101959	61.57	3.46	5.00	1.72	2.16	1.56	$ 82,095	$ 30,500	$ 1,790
160	6656	PWOPRSED0001405	WLNE101691	60.7	4.54	5.00	1.72	2.16	1.44	$ 277,321	$ 47,850	$ 37,276

Project ID	ID			Condition			COF			Capital Project Cost (Replacement)		
	Road Segment ID	Sewer Asset_ID	Water OID	Road	Sewer	Water	Road	Sewer	Water	Road	Sewer	Water
186	6534	PWOPRSED0001889	WLNE103538	40.79	4.46	5.00	1.78	2.88	1.50	$ 60,328	$ 41,450	$ 37,975
194	6677	PWOPRSED0002761	WLNE101697	30.36	4.54	5.00	1.66	2.72	1.38	$ 78,949	$ 13,100	$ 43,635
209	6662	PWOPRSED0002921	WLNE101667	30.36	4.54	5.00	1.60	1.92	1.44	$ 68,138	$ 13,550	$ 2,748
210	6662	PWOPRSED0002921	WLNE101693	30.36	4.54	5.00	1.60	1.92	1.44	$ 68,138	$ 13,550	$ 21,080
215	6549	PWOPRSED0001983	WLNE101959	40.79	5.00	5.00	1.60	2.28	1.56	$ 108,183	$ 30,400	$1,790
158	6679		WLNE103527	30.36	0.00	5.00	1.96	0.00	1.56	$ 66,981	$ -	$1,930
230	6670	PWOPRSED0002760	WLNE101694	30.36	4.54	5.00	2.20	2.96	1.56	$ 79,554	$ 41,750	$ 47,185
231	6670	PWOPRSED0002761	WLNE101694	30.36	4.54	5.00	2.20	2.72	1.56	$ 79,554	$ 13,100	$47,185
250	6661	PWOPRSED0001407	WLNE101667	60.7	4.54	5.00	1.72	2.16	1.44	$ 272,581	$ 35,600	$ 2,748

The Cash investment required for each of the projects is listed in Table 6-22. All these projects are required at the same budget year. The cash available for investment is $ 540,000 (divided as follows; Road: $300K, Water: $ 120K, and Sewer: $ 120K).

The goal is to find the projects that maximize the risk reduced per net present value of dollars spent in investment over the life cycle of these assets. The optimal solution in Table 6-23 indicates that the City can obtain a maximum Risk reduced / $ spent of 48.3 by selecting a total of twenty projects. These projects consume only $523,080 (Road: $295.8K, Water: $109.6K, and Sewer: $117.7K) of the available budget, with $16,920 (Road: $4.2K, Water: $10.4K, and Sewer: $2.3K) left over. However, the remaining $16,920 is an insufficient amount to invest in any of the remaining projects.

Table 6-23 Limited Budget Example Optimal Solution

	Investment Options (1 -yes or 0- No)							Output	
Project ID	S1- Road	S2-Sewer	S3-Water	S4- Water/ Road	S5-Sewer/Road	S6-Water/ Sewer/ Road	S7-Water/Sewer (trenchless)	Risk/$spent	Sum Project cost
31	0	1	0	0	0	0	0	2.13	$ 28,300.00
34	0	0	1	0	0	0	0	1.52	$ 24,820.00
35	0	0	1	0	0	0	0	1.58	$ 20,380.00
42	0	0	0	1	0	0	0	1.94	$ 4,355.45
66	0	0	0	0	0	0	0	0.00	$ -
67	0	0	0	0	0	0	0	0.00	$ -
68	0	0	0	0	0	0	0	0.00	$ -
69	0	1	0	0	0	0	0	2.75	$ 11,150.00
74	0	0	1	0	0	0	0	3.16	$ 15,927.50

Project ID	Investment Options (1 -yes or 0- No)							Output	
	S1- Road	S2-Sewer	S3-Water	S4- Water/ Road	S5-Sewer/Road	S6-Water/ Sewer/ Road	S7-Water/Sewer (trenchless)	Risk/$spent	Sum Project cost
75	0	0	1	0	0	0	0	3.16	$ 15,927.50
546	0	0	0	1	0	0	0	2.90	$ 27,084.15
320	0	0	0	1	0	0	0	2.42	$ 14,200.80
76	0	0	1	0	0	0	0	3.16	$ 15,927.50
77	0	1	0	0	0	0	0	2.75	$ 11,150.00
137	1	0	0	0	0	0	0	1.87	$105,951.60
140	0	0	0	0	0	0	0	0.00	$ -
147	0	0	1	0	0	0	0	1.54	$ 1,790.00
160	0	0	0	0	0	0	0	0.00	$ -
186	1	0	0	0	0	0	0	1.02	$ 60,327.58
194	0	1	0	0	0	0	0	2.43	$ 13,100.00
209	0	0	0	1	0	0	0	1.58	$ 10,416.19
210	0	1	0	0	0	0	0	1.71	$ 13,550.00
215	0	0	0	0	0	0	1	3.36	$ 28,971.00
158	0	0	0	1	0	0	0	1.94	$ 4,349.51
230	1	0	0	0	0	0	0	1.49	$ 79,553.71
231	0	1	0	0	0	0	0	2.43	$ 13,100.00
250	0	0	1	0	0	0	0	1.42	$ 2,747.50
							Total∑	**48.28**	**$523,079.99**

6.3.1 ODM Model Sensitivity Analysis

(i) Sensitivity Analysis for Budget Constraints

Further sensitivity analysis to the above budget constraints example was performed. Table 6-24 below shows how the Risk reduced / dollar spent index varies as the budget changes. As the budget increases, the number of integrated projects increases as it yields a higher Risk/$ spent index but at a higher initial investment. As shown in the table below at a budget of $2.025 million the total number of integrated projects (i.e. S4, S5, S6, and S7) was nineteen (19), while the original budget has recommended only six (6) projects. Also, the total number of projects was reduced to 22 instead of 27.

Table 6-24 Limited Budget Example Sensitivity Analysis overview

Budget	Amount Invested	Total Risk reduced / $ spent (NPV)	Sensitivity analysis (No of projects)							Total No. of projects
			S1- Road	S2-Sewer	S3-Water	S4- Water/ Road	S5-Sewer/Road	S6-Water/Sewer/ Road	S7-Water/Sewer (trenchless)	
$2,025,000	$2,024,237	73.2	**0**	**4**	**4**	**7**	**2**	**7**	**3**	27
$1,755,000	$1,722,645	72.1	**0**	**5**	**6**	**6**	**2**	**6**	**2**	27
$1,350,000	$1,337,855	69.6	**0**	**8**	**7**	**9**	**1**	**1**	**1**	27
$1,000,000	$981,995	63.0	**3**	**4**	**7**	**8**	**4**	**0**	**1**	27
$675,000	$652,165	53.3	**3**	**5**	**7**	**8**	**1**	**0**	**0**	24
$540,000	$523,080	48.3	**3**	**6**	**7**	**5**	**0**	**0**	**1**	22
$405,000	$394,149	43.4	**2**	**5**	**7**	**5**	**1**	**0**	**0**	20
$270,000	$267,445	34.9	**1**	**3**	**4**	**5**	**2**	**0**	**0**	15
$135,000	$122,076	22.8	**0**	**2**	**2**	**6**	**0**	**0**	**0**	10

Figure 6-24 shows the risk reduced per dollar spent versus Budget. Clearly the city can achieve a larger risk/$ spent index with a larger budget. At the current budget ($0.54M) the total risk reduced / $ spent is 48.3 while this index can reach 69.6 with 2.5 times the current budget (i.e. $1.35 M).

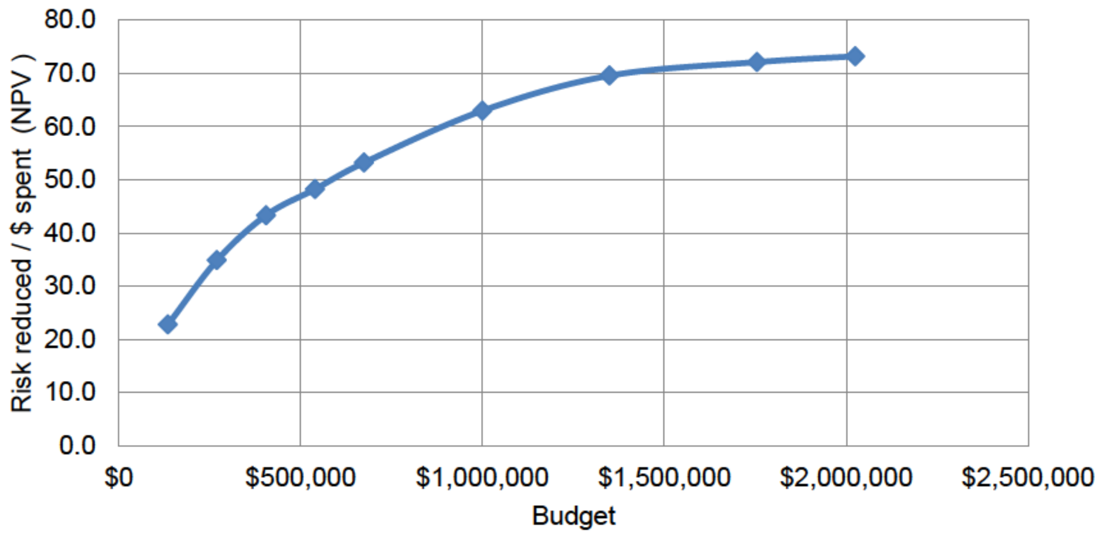


Figure 6-24 Total Risk Reduced versus Budget

While the objective is to maximize the risk reduced per dollar spent, there are other factors that need to be taken into consideration throughout this decision-making process. A detailed analysis of the economic loss and future network condition was performed to provide a greater context to this problem as shown in Table 6-25.

Table 6-25 Limited Budget Example Sensitivity Analysis Details

				Average Network Condition		
Budget	Percent Change In Budget	Economic Loss	Economic Loss /Budget	Water	Sewer	Road
$2,160,000	400%	$211,888	9.8%	1.6	1.7	82.2
$1,755,000	325%	$178,028	10.1%	2.0	2.0	78.0
$1,350,000	250%	$104,988	7.8%	2.3	2.5	71.5
$1,000,000	185%	$72,904	7.3%	2.7	2.8	73.1
$675,000	125%	$48,302	7.2%	2.8	3.2	72.6
$540,000	100%	$39,460	7.3%	3.0	3.0	65.0
$405,000	75%	$30,504	7.5%	3.2	3.2	64.6
$270,000	50%	$14,327	5.3%	3.4	3.5	62.3
$135,000	25%	$7,438	5.5%	3.8	3.7	58.5

As discussed in Chapter 3 the main purpose of Economic Loss analysis is to estimate the economic loss / gain of fixing the date of the intervention of road, sewer and /or water segment in comparison to intervention at optimal replacement time. Figure 6-25 shows the Economic Loss versus Budget, there is an upward trend in the economic loss versus budget. At the current budget, the economic loss as a result of coordinating six projects is around $39.4 thousand (7.3% of current budget). If the budget is increased to $2.16 M (i.e. 4 times the current budget) the economic loss will rise to $211.9 thousand (9.8% of increased budget) but the number of coordinated projects will increase to 19 instead of 6.

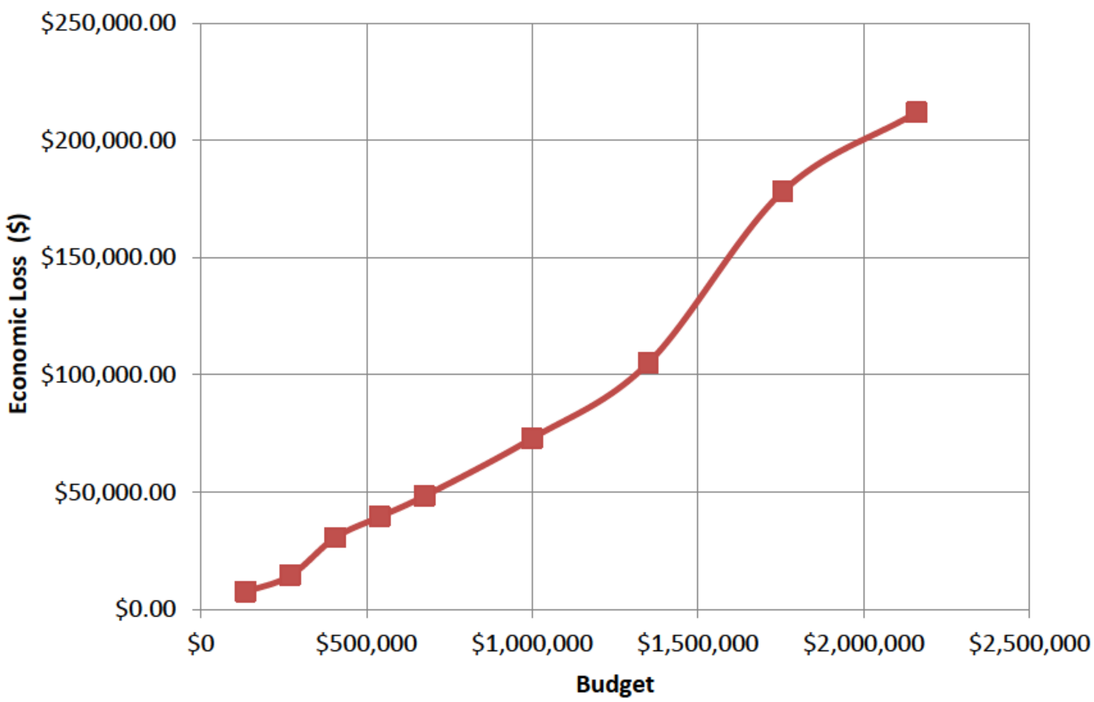


Figure 6-25 Total Economic Loss versus Budget

Figure 6-26 shows the average network condition versus budget for water and sewer in the left Y-axis and roads in the right secondary Y-axis. It can be clearly seen that the overall network condition rating for both water and sewer was declining as the budget increased (water and sewer condition of 1 is very good and condition of 5 is very poor, therefore a downward curve is preferred). On the other secondary Y axis the road average network condition (road condition- PCI index- of 100 is very good and condition of 0 is very poor, therefore an upward curve is preferred) has increased sharply as the budget increased from $135,000 to $675,000 then remained stable while both water and sewer average condition increased, which indicates more water and sewer projects were recommended. Finally, as the budget increased from $1.4 M to $2.16 M, the average road network condition increased again but more steeply than $0.7 M to $1.4 M range until reaching its peak budget amount of $2.16M.

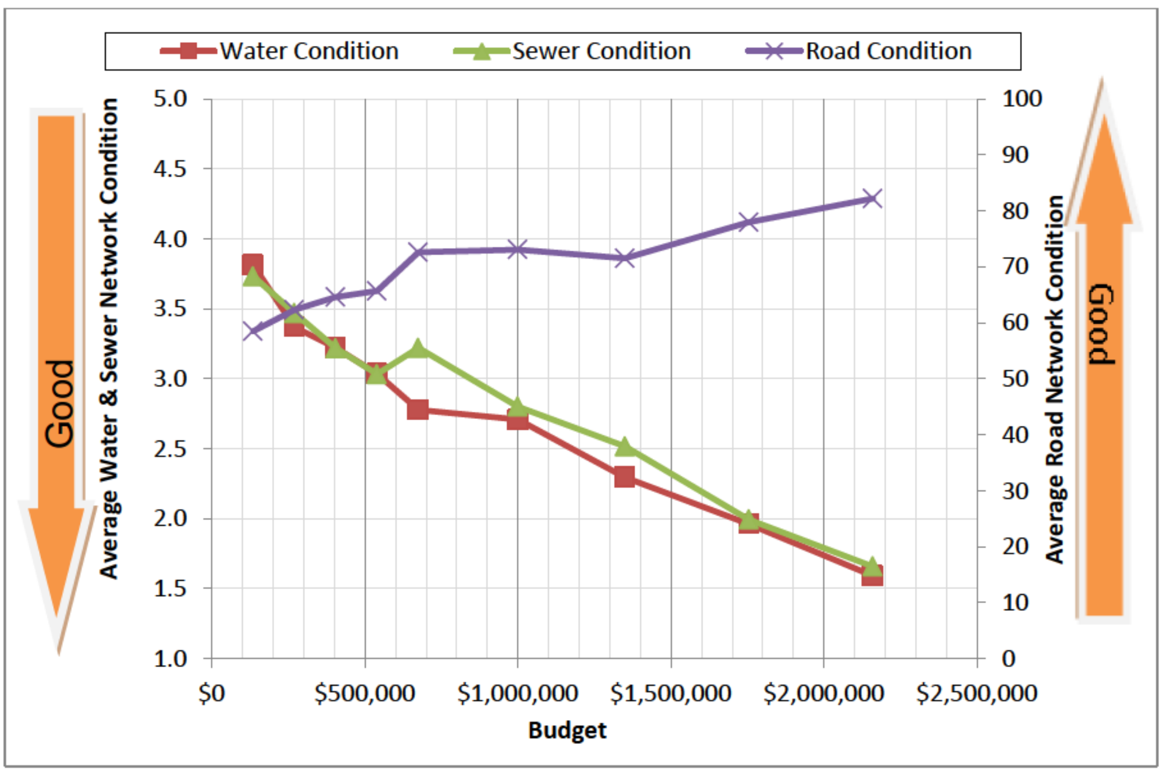


Figure 6-26 Average Network Condition versus Budget

In conclusion, as the budget increased the number of integrated corridor rehabilitation increased, risk reduced per dollar spent increased and the average network condition improved. On the other side the amount of initial cash investment required increased and the economic loss increased. Finally, the developed ODM model provides an easy and informed decision-making approach to assist decision makers with corridor rehabilitation project selection process.

(ii) Sensitivity Analysis for Condition Constraints

To determine the true impact of changing the condition information on the total number of integrated projects and the risk reduced per dollar spent, sensitivity analyses was then performed. Sensitivity analysis progresses by relaxing all constraints, and changing the upper and lower limits of the average network condition, then compare the input constraints limits with the objective function output results and the total number of recommended projects. This was done for each Asset class separately, the first iteration was performed by changing the water condition limits to be between 1 and 1.5 , and other constraints were as follows: budget constraints range ($0 - $4.5M), CDPM range (1-10), road condition range (50 - 100) , and sewer condition range (1-5). Then, the second iteration was established by changing the water constraints range to 1.5-2.0 while all other constraints remained the same. Similarly, the same approach was used for sewer and road conditions sensitivity analysis.

Figure 6-27 shows the risk reduced per dollar spent of recommended corridor rehabilitation projects for the average water and sewer network condition. As an overall trend, it is clear that the risk reduced / $ spent decreases as the average network condition increases. There has been a moderate decline from 76 to 72 (7.6%) in the risk reduction value as water average network condition increased from 1 to 4. On the other hand, the risk reduced/$spent has dropped considerably from 76 to 65 (14.4%) as sewer average network condition increased from 1 to 4. The graph below shows that the risk reduced /$ spent was slightly decreasing until average network condition between 2 - 3 and it has then dropped to reach its lowest levels for both water and sewer average network conditions.

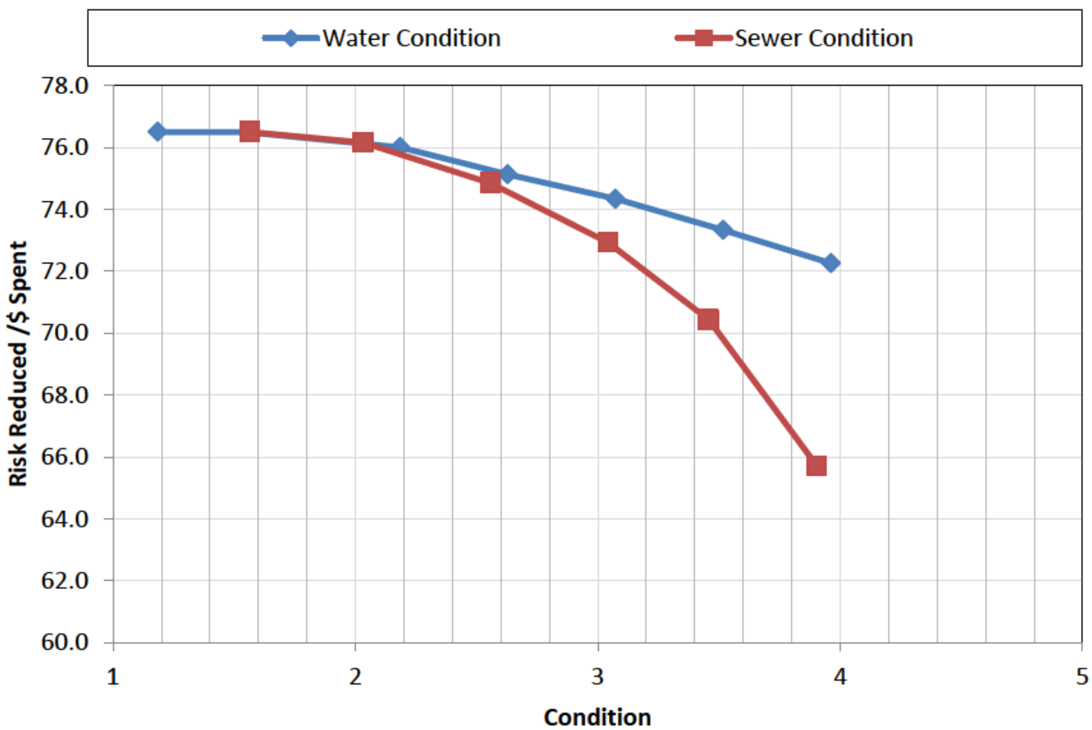


Figure 6-27 Average Water and Sewer Network Condition versus Risk Reduced

Similarly, Figure 6-28 shows the risk reduced per dollar spent versus road average network condition. It can be noticed that the risk reduction has increased from 67 to 76 (13.4%) as road average network condition increased from 50 to 100.

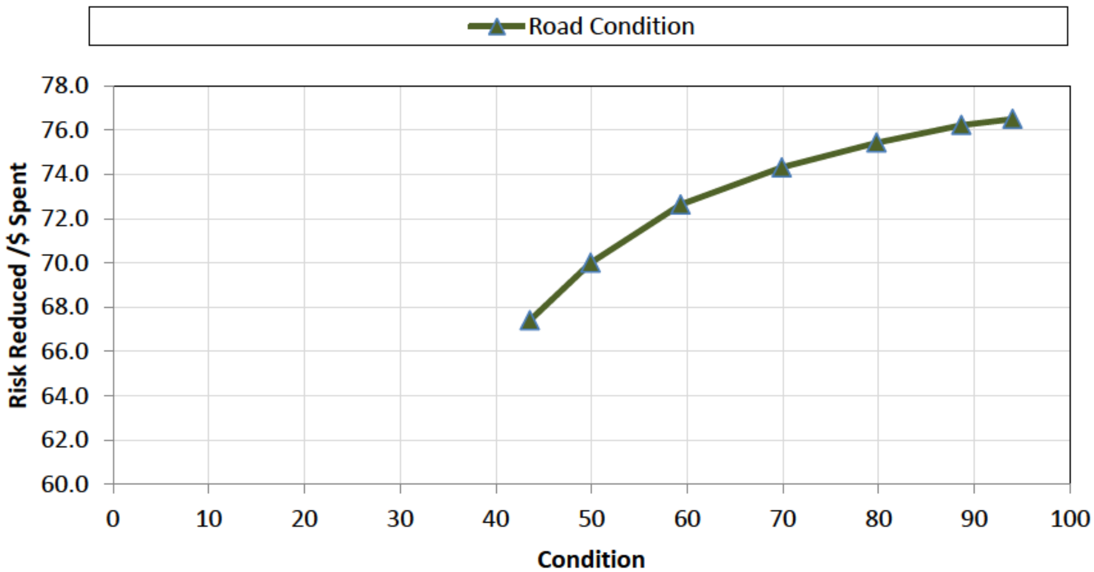


Figure 6-28 Average Road Network Condition versus Risk Reduced

The other important aspect of the above condition sensitivity analysis is the number of integrated corridor rehabilitation projects recommended during each iteration of this process. The following bar charts Figure 6-29, Figure 6-30, and Figure 6-31 show the number of corridor rehabilitation projects against the average network condition for water, sewer and road respectively. Through analyzing those figures there are a few findings that can be highlighted.

As shown in Figure 6-29, when the average water network condition was constrained between 1-1.5 the total number of integrated water projects (i.e. S4-Water/Road, S6- Water/Sewer/Road, and S7-Water/Sewer trenchless) was at a peak with a total of 25 projects recommended out of the total 27 projects evaluated. Noting that, water condition constrained between 1-1.5 means that most watermains evaluated should be in very good or fairly new conditions.

Additionally, there were zero "S1- water only" projects recommended. This scenario has yielded the highest risk reduced /dollar spent for the water condition sensitivity constraints as discussed earlier and shown in Figure 6-27 above.

As the constraints intervals were tightened the number of water projects decreased and on the other side sewer and road project increased. As shown in Figure 6-29 the "S4- Water/ Road" and "S6- Water/Sewer/Road" recommended projects decreased from 9 & 13 to 3 & 4 respectively as the water condition constraints changed from " 1.0-1.5" to "4.0-4.5", while the optimization process comprised by recommending about 20 projects of "S5- Sewer/Road" instead of zero to maximize the risk reduction objective function. This has resulted in a lower risk reduction /$ spent score.

By analyzing the same figure it was noticed that by changing the water condition constraints the total number of recommended water projects decreased significantly. For instance, when the water condition was constrained to "1.0-1.5" the total number of water related projects recommended was 25 (i.e. alternatives no. S4 & S6 & S7) then the number of water related projects gradually dropped to 4 (i.e. alternatives no. S6) when these constraints changed to "4.0-4.5" interval.

A similar trend was evident for the sewer condition constraints as shown in Figure 6-30. For example, as the sewer condition changed from "1.0-1.5" to "4.0-4.5" intervals, the number of sewer related projects has slumped from 18 (i.e. alternatives no. S2 & S6 & S7) to 1 project (i.e. alternatives no. S6).

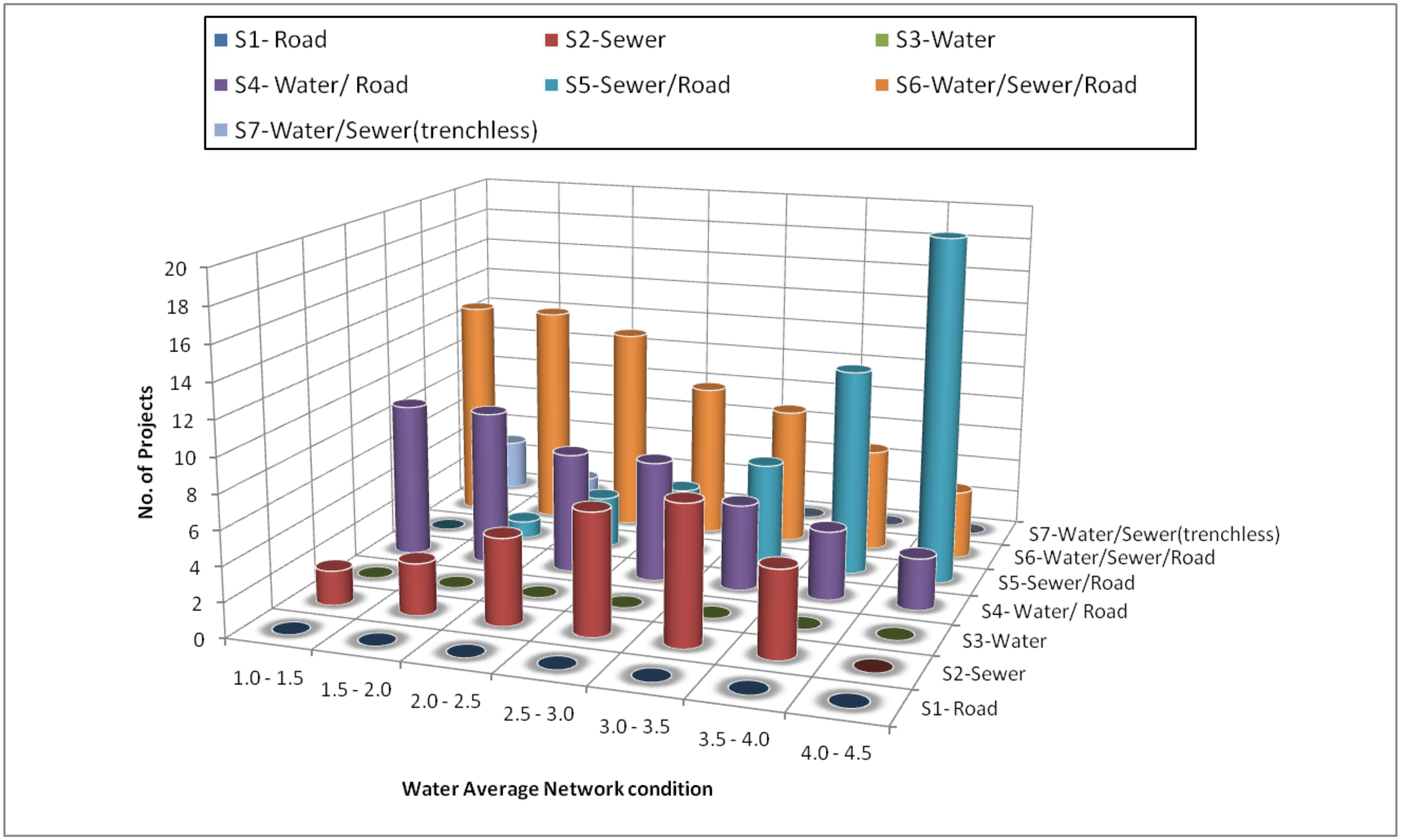


Figure 6-29 Number of Corridor Rehabilitation Project versus Water Condition Constraints

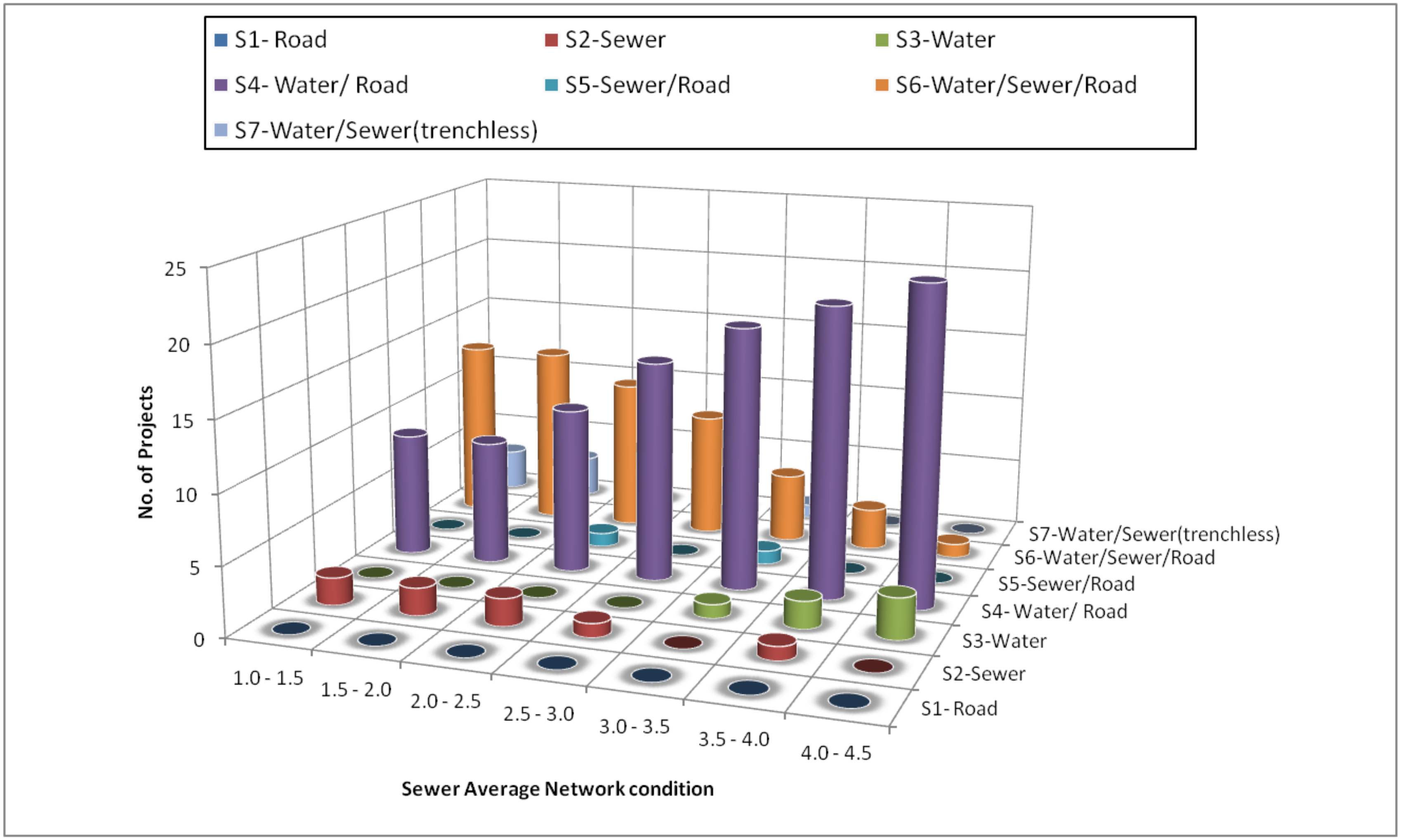


Figure 6-30 Number of Corridor Rehabilitation Project versus Sewer Condition Constraints

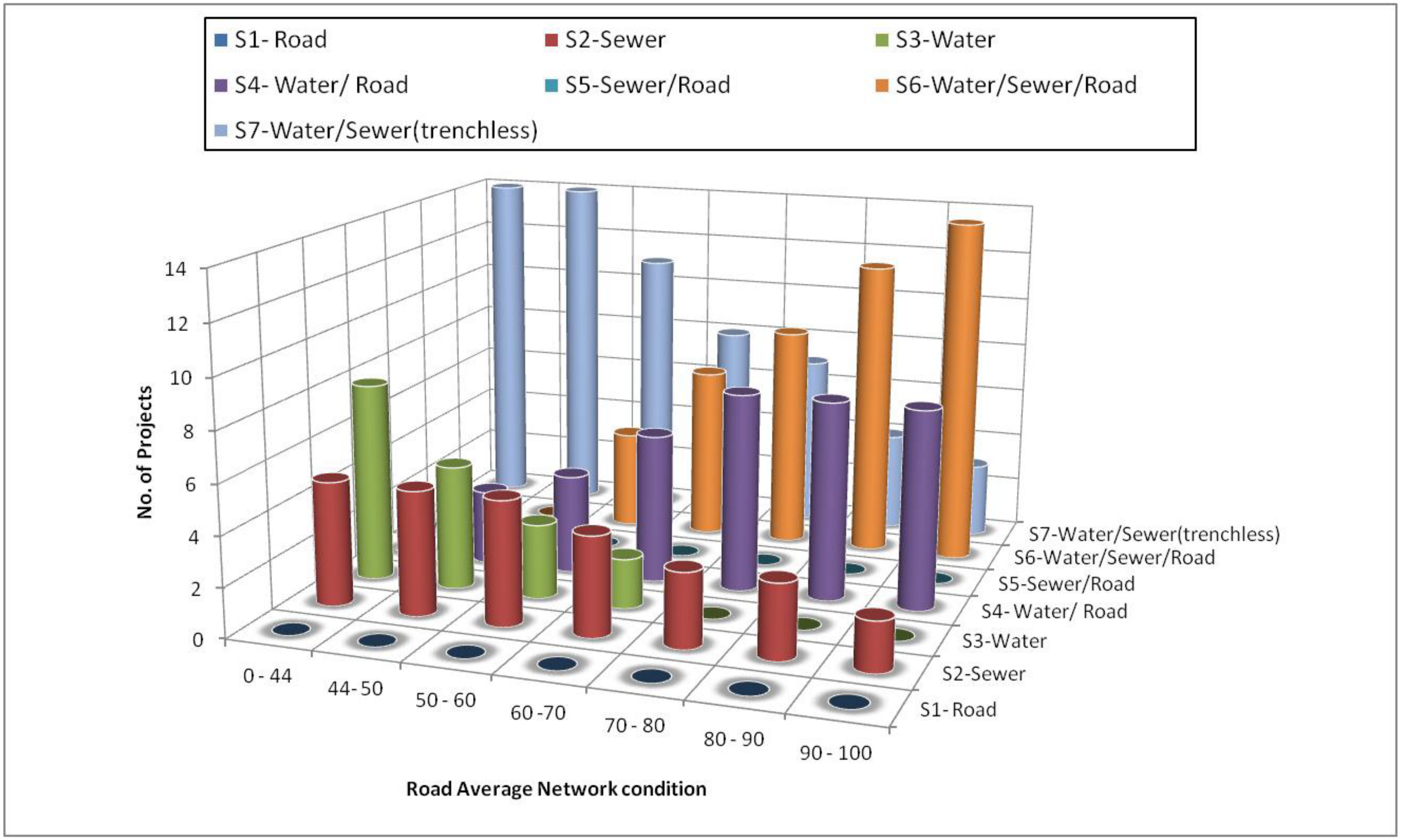


Figure 6-31 Number of Corridor Rehabilitation Project versus Road Condition Constraints

Similarly, the road network condition charts showed a comparable trend to water and sewer charts as shown in Figure 6-31. The difference was the road condition index was in converse to the water and sewer index. Specifically as the road condition index (PCI) increases from 0 to 100, the condition of the road segment is improved, such that when a new road segment is built the initial condition of this road would be 100 and it deteriorates over time to zero. As shown in Figure 6-31 the road condition changed from "0-44" to "90-100" intervals, the number of road related projects has climbed from 0 to 22 project (i.e. alternatives no. S4 & S6).

In conclusion, as the average network condition constrains for water, sewer, and road improves (i.e. water & sewer condition rating decrease, and road condition rating increase) the risk reduced per dollar spent increases and the number of recommended corridor rehabilitation projects also increases.

(iii) Sensitivity Analysis for CDPM

The sensitivity analysis for CDPM index was performed by changing the CDPM constraints from 1 to 10 and recalculating the risk reduced output values. The risk reduced per dollar spent results were indifferent to the change in CDPM constraints. The main reason was that the sample provided for CDPM index had the same initial values. This constraint was introduced mainly to ensure that any asset with poor customer driven performance is flagged and considered in the capital planning.

(iv) Sample Sensitivity Analysis for Condition Values

A further sensitivity analysis for the initial condition values was performed to determine the impact of changing the current condition on both the risk reduced and number of corridor rehabilitation projects selected. All input values were the same as the above example. The first iteration was performed by changing the water by 10% less than current condition (i.e. condition changed from 5 to 4.5), the constrains were as follows: budget constrains range ($0 - $4.5M), CDPM range (5-10), road condition range (65 - 90) , water condition range (2.5-5) and sewer condition range (2.5-5).

Results showed a 25% decrease in the risk reduced per dollar spent index when the water condition reduced by 50%. As shown in Figure 6-32 the relationship between risk reduced and water condition is non-linear. The curve has decreased rapidly once the water condition was reduced by more than 30%.

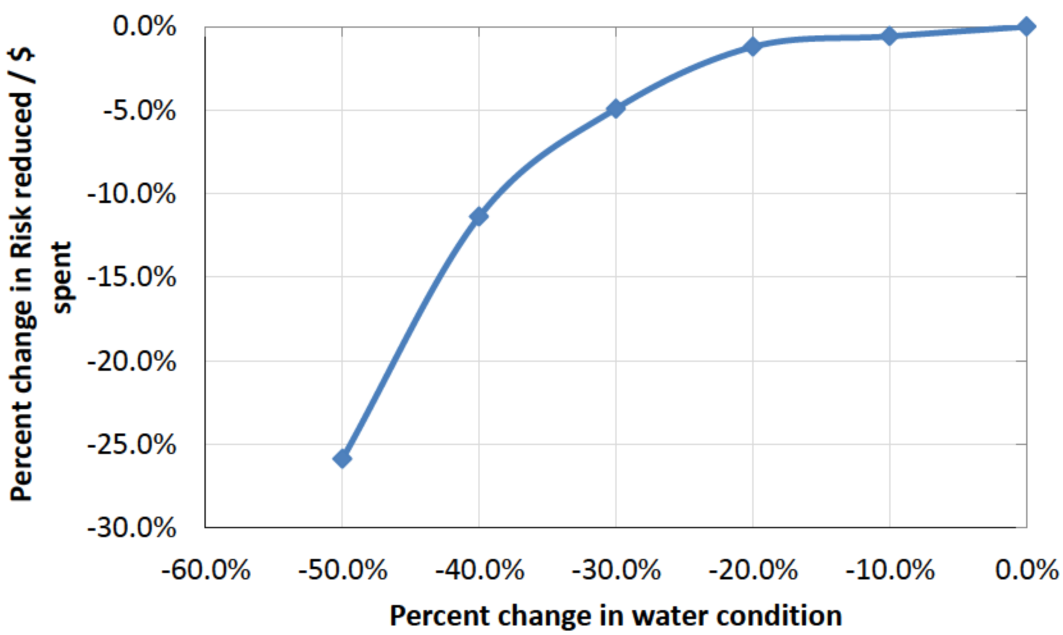


Figure 6-32 Risk Reduced versus Water Condition Sensitivity Results

A more detailed analysis of the number of integrated projects showed the number of integrated projects reduced from 21 to 5 (-76%) as shown in Figure 6-33. While the number of water exclusive projects were reduced from 16 to 0 (-100%), as the water condition constraints was satisfied by not allowing any good condition water assets recommended for rehabilitation/ replacement .   Similar results were obtained from the sewer and road condition Sensitivity analysis.

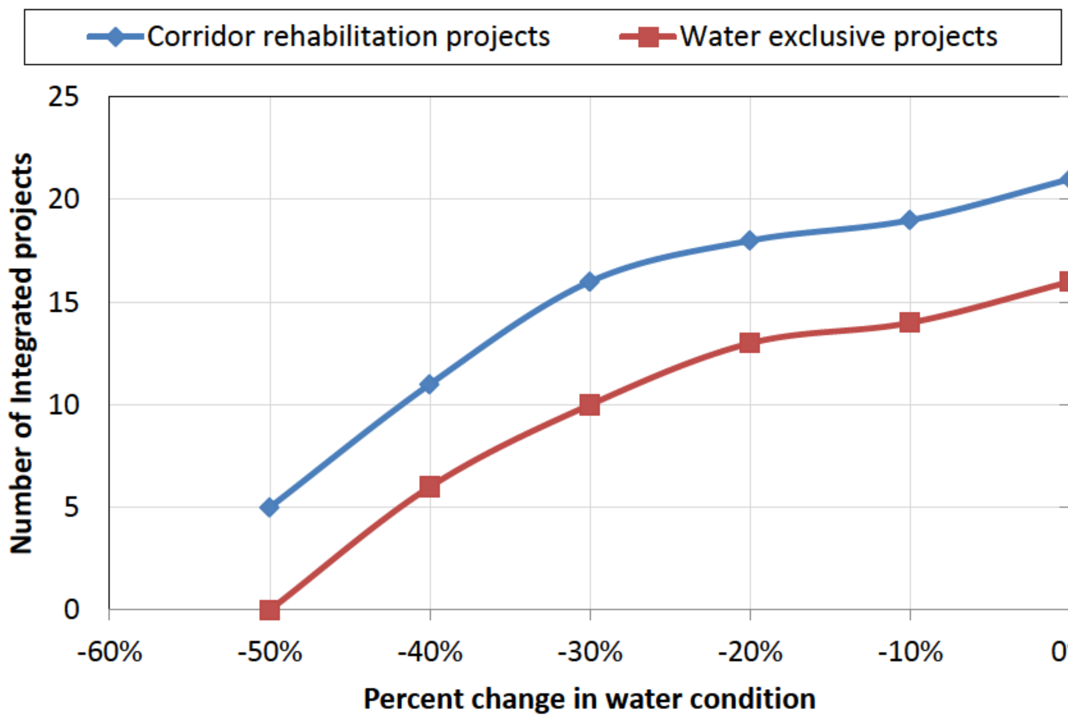


Figure 6-33 Number of Integrated projects versus Water Condition Sensitivity Results

In summary, the developed ODM model proved to react consistently to changes in the condition values and constraints thereby providing a quick and easy tool to identify and prioritize candidate project for corridor rehabilitation.

6.4 Evaluation of the Proposed Methodology

The developed models were designed in a way that can be implemented separately or combined. For example, the municipality can elect to adopt one or more of the developed tools (Risk model, CDPM model, or the ODM model). The evaluation and validation of the developed model is implemented through a consultation with asset managers from (City of Guelph, Region of Peel, and City of London). Recently, both region of peel and the City of London have been working on implementing a corporate asset management program for managing various municipality owned assets including road, water and wastewater networks.

Asset manager's feedback was highly positive; they showed interest in the approach and the model. Currently, most municipalities are moving towards a risk based decision-making as a tool to optimize decision-making across various asset classes. Additionally, the concept of defining, tracking, and monitoring customer driven level of service is currently being deliberated by various municipalities. For example, various municipalities has recently adopted a service based budgeting approach to enable tracking and allocation of resources based on customer needs. The City of London has adopted a similar risk based decision-making approach, proposed in this dissertation, and is currently assessing further implementation of the proposed integration methodology. On the other hand, Region of Peel is currently working on defining the customer driven performance measure (Customer Level of Service) and considering the adaptation of the proposed economic loss calculation tools, proposed in this dissertation, to further enhance their optimized decision-making practice.

Therefore, the methodology and the tool have proven to have the potential to be used as an integrated decision-making support tool for major municipal infrastructure.

6.5 Implementation Challenges and Key Lessons Learned

Preliminary analysis of the workshop results combined with the findings of the in-depth interviews with various municipal sector employees and asset managers illuminated the following implementation challenges and key lessons:

a) Asset Inventories

The duplication of data across multiple locations in the organization results in an increased cost to maintain the current information in multiple locations. A review of the existing data helps identify any data duplicated across multiple databases throughout the municipality which in turn, improves efficiency and reduces costs to collect, store and update corporate data.

Maintaining/updating of metadata (data about the data) is not a common practice for the road, watermain and/or sewermain attributes. It is recommended that municipalities strive to maintain a more rigorous documentation procedure for their metadata to improve quality and reliability of information the data is used to create.

The quality and value of available data differs significantly across multiple databases where it is kept. This may result in unreliable data and therefore unreliable information crafted from its use. Data quality should be evaluated, tracked and managed regularly.

Data is not always readily available in a usable format. Data has to be available through an effective portal, for example, a web interface or a software application, to support proper execution of the integrated decision-making approach. Manual or hardcopy systems are insufficient for this purpose.

Segmentation of road / water/ sewer assets is inconsistent. Currently, most municipalities use three different segmentation schemes that are not linked or cross-referenced in GIS. This increases the complexity of the network level analysis, it does not streamline or improve the way in which optimization results are interpreted and converted into projects. Example of an effective approach is to maintain link and /or consolidate those three schemes into one consistent segmentation approach. Currently, the City of Hamilton, Ontario is developing a new GIS layer shape file that aims on integrating and consolidating the three segmentation schemes into one scheme.

b) Risk Assessment

Risk assessment practices vary across municipalities. Each municipality has a different understanding of its risk exposure and impacts. Risks arises from the potential for events or failures to occur and, along with other factors discussed earlier, will vary depending on the location, operating regime, capacity, age, condition of the asset, etc. It is important to develop a clear picture of the risk profile of the asset base in order to better understand which assets are in most need of attention.

The lack of asset management framework to guide municipalities has resulted in inconsistency in the level of maturity of each department within the same municipality. For example, roads may have a regular condition assessment program (proactive) while watermains and /or sewermains will only investigate an incident after it occurs (reactive) or on an ad hoc basis. Generally, departments cannot compare risk assessments for their assets inhibiting the ability to make integrated decisions that would improve any operating/maintenance or capital program.

Some municipalities lack an asset specific risk management policy. Risk is managed through maintenance practices and design standards which are legislation driven. Formulization of a risk-based approach will support the implementation of an effective integrated decision support system. It is recommended to conduct an annual review of the identified risk factors, and record other risks as they are identified.

c) Performance evaluation (level of service)

Workshop participants believed that they need to improve tracking the level of service provided to their customers; generally they track various performance measures that can be defined as, or used to establish, levels of service.

Municipalities fully understand the technical or asset specific level of service (e.g. water pressure, % of equipment down time, no. of sewer collapses, % pothole repairs, etc.), but with respect to customer level of service there is little information available to fully establish those measures. There is no specific rule for customer level of service identification, but generally there is high customer expectations (i.e. customer expect 24/7 service). On the other hand, the customer is not always aware that there are some services only provided based on complaints received; no filed complaints results in no service provided (e.g. street light replacement, minor pothole repairs, etc.). There is always a trade-off between the service provided to customers and the willingness to pay for this service by the customer.

d) Program Optimization and Project Alternatives Evaluations

Decision makers emphasized on the importance of optimized decision-making tools. “Need more informed decision-making” said by most interviewed asset managers/asset owners.

In order to be able to coordinate and optimize corridor rehabilitation plans, all three R/W/S departments should plan projects within the same relative time horizon (e.g. generate a 3-5 year plan) thereby enabling effective integration and coordination of corridor rehabilitation projects. The coordination of the construction of road, sewer and water projects practise has proven to be most effective, but lack of risk based decision-making protocols to govern this coordination can have unforeseen consequences. For instance, the worst condition asset (e.g. sewer) may not be replaced because the collocated asset (e.g. road and water) is in good condition or recently addressed. This situation could be mitigated if municipalities had an established risk based decision-making approach for corridor rehabilitation decisions.

Budget deliberation is conducted annually by Council. Administration recommends a list of candidate projects that provide the highest benefits to municipalities. Some political agendas may alter the recommended list, which would result in projects unnecessarily being advanced or deferred to the next planning cycle. This will have a high impact on the city's risk exposure and /or investment requirements. Experts believe that lack of information provided to public officials is one of the main reasons for this issue. For example, when presenting a consistent “scorecard” that would include (current condition, risk exposure, current level of service, projects cost, and risk reduced per dollar invested, economic loss/ gain, etc.) will help further the business case and educate the public and officials about the impact of advancing or deferring a decision to repair/replace any asset. There is a strong political influence on the tax based asset (e.g. roads) decisions versus the need to meet safety standards and customer expectations.

Segmentation and spatial limits of rehabilitation / replacement represent a major challenge for project alternatives evaluation and /or selection. This consideration is determined by the municipality's policy on the spatial extents of rehabilitation / replacement, usually in the form of a minimum length that they will replace / rehabilitate. For example, some municipalities will only replace from intersection to intersection for roads, and along the entire length of a city block for watermains / sewermains; while other municipalities will replace short lengths of road and / or mains to reduce the long-term cost of sustaining the entire infrastructure network.

Addition of social and environmental cost to projects is a practice currently being considered by various municipalities to limit or eliminate unnecessary construction within the road right of way. This would be achieved by implementing "road lane rental" charges. This is a fee charged by municipalities to various utilities for allowing them to cut the road for maintenance of their utilities (e.g. cables, gas, building, etc.). This fee can be also charged for other assets owned by the municipality that are located within the road right of way (e.g. storm, sewer, water)

e) Organization structure

Municipalities are generally organized into numerous departments, divisions, and/or service areas that serve as independent functions (silos). There is low interest in sharing information, collaborating, strategizing, or interacting across these individualized functions. Communication and sharing of information between operational departments (i.e. water, sewer, and roads) increases staff awareness of cross-functional activities, integration opportunities and their individual department's contribution to the success of the entire organization. At large, most municipalities emphasize the importance of asset management to provide a better communication tool and bridge historically isolated functions.

Culture change is necessary to implement integrated asset management framework effectively. Integration requires cross discipline collaboration within departments and across various asset types. Municipalities must engage the entire organization in the value of an integrated asset management approach.

There is a need to generate interest and buy-in to the integrated asset management approach, to enable leadership advocacy.

Most decision-making procedures related to maintenance, rehabilitation and /or replacement are not readily available. There are some policy and procedure documents, but business process charts (including who knows what; who to ask about what, etc.) are not documented. Benchmarking initiatives similar to OMBI (2010) provides a critical first step for municipalities to understand the implementation challenges faced by others and create effective policies to address integrated decision- making for municipal infrastructure.

The corridor rehabilitation process should possibly be supported or operated by a coordination committee (e.g. Utility Coordination Committee (UCC)). This coordination committee could potentially include parties from a wide variety of stakeholders; federal, provincial, municipal, or a private utility (e.g. EPCOR, who manages water and wastewater networks in Edmonton, AB). In the future, corridor rehabilitation, where all infrastructure assets in a corridor (e.g. a road, water, sewer, cables, gas, etc.) are upgraded at the same time, can be set as a standard practice administrated by this type of committee.

6.6 Summary

A case study was selected as a proof of concept and for the purpose of testing the model. These modules were implemented on the city of Guelph road, watermain, and sewermain sub network. Optimization results showed that the maximum risk reduced / dollar spent was achieved by utilizing one or more corridor rehabilitation option (e.g. road /water/ sewer 36%, Road/sewer 23%, Road/water 25%) when the budget is unrestricted. Further sensitivity analysis to the budget constraints showed that the Risk reduced / dollar spent index varies as the budget changes. The numbers of recommended corridor rehabilitation project were significantly decreased as the budget decreases. Clearly, the city can achieve a higher Risk reduction / dollar spent index with a higher budget. Also note that as the budget increases, the number of integrated projects increases as it yields a higher Risk/$ spent index but at a higher initial investment cost.

Asset managers were asked to evaluate the proposed model and approach. The feedback was highly positive as they showed interest and considered adopting the proposed approach in their municipalities. This chapter also highlights the major implementation challenges and lessons learned through the development and implementation phases of the integrated asset management framework.

CHAPTER 7: CONCLUSION, CONTRIBUTIONS AND RECOMMENDATION

7.1 Conclusion

This research proposes a decision-support framework for integrated asset management of road network, water distribution network and wastewater distribution network. It all started by undertaking a review of the state of art and practice in asset management, risk assessment, performance assessment and decision-making approaches of core municipal infrastructure and identified the major gaps in current practice for integrated corridor rehabilitation. Researching existing knowledge was established through literature reviews, workshops with experts from public and private sector, and access to published and non-published reports / documents provided by workshop participants. The results of this literature review are summarised in Chapter 2. The research methodology is based on developing an Integrated Risk Assessment framework, evaluation of Client/ customer Driven Performance Measure, then develop decision support model (prioritization using optimization).

The Integrated Risk Assessment (IRA) framework was developed; it predicts and assesses the probability of failure and consequence of failure of an integrated road segment, watermain, and sewermain asset. Eighteen factors within four main parameters (economic, environmental, operational, and social impacts) are used to represent the consequence of failure assessment process. The relative weight of each factor within each consequence of failure parameters was calculated using a Delphi – AHP process. The economic parameters have the highest impact on assets consequence of failure with a relative weight of (39%) followed by operational and environmental, social parameters with a relative weight of (27%, 21% & 13%) respectively. Detailed results show that pipe/ road size factors have the highest effect on overall Consequence of Failure index (11.7%), then accessibility (10.9%); however, the third factor is environmental sensitive area (9.9%). The probabilities of failure were established based on existing condition information and then assigned a probability of failure value between (0.01-1). Once probability of failure and consequence of failure were calculated for each individual asset, the outcomes are then integrated via "K-mean" clustering technique - using its unsupervised learning algorithms - to assign an overall integrated risk index for the combined segment. A sensitivity analysis was performed to determine which factors have the highest impact on the risk model. Results show that Economic factors have the highest impact on the overall risk index.

Secondly, a Client / Customer Driven Performance Measure (CDPM) model is developed to assess the customer level of service performance of an integrated road segment, watermain, and sewermain asset. Nine customer performance measures are used to represent the CDPM assessment process. The model was established using fuzzy logic technique. Results showed that road Roughness Rating (RPI) has the highest impact on CDPM index followed by number of watermain interruption (breaks) then sewermain capacity issues. Sensitivity analysis results shows that road roughness rating has the highest impact on the overall CDPM index results and it has the steepest slop.

The third developed model was the optimized decision-making (ODM) model of various integration options. This optimization model was developed using integer-programming algorithm. This model utilizes the available replacement / rehabilitation alternatives, setting priorities for integrated corridor rehabilitation, implementing optimization of renewal cost and defining the best replacement interval. The optimization model objective was to maximize the risk reduction for minimum net present value of investment cost subject to condition, CDPM, and budget constraints.

Finally a prototype tool "Integrated Decision Support System" (IDSS) was developed and implemented. The IDSS was developed using the visual basic applications (VBA) programming and applied as a set of applications that are Microsoft Access and Excel based. The developed system applications were designed to be easily linked to Esri Arc-GIS for geographical representation. The developed system architecture is composed of three modules and a central asset registry database. As discussed in chapter 5, each module contains some processes and there are some mutual relations between the modules which illustrate how they are linked together.

A series of Workshop setting interviews were conducted with various municipalities' departmental staff to gather all necessary information for framework development. A case study has been utilized from the City of Guelph, Ontario, Canada. The proposed framework requires City staff to work together to develop a shared database of asset inventories, condition, performance and financial information to support decision-making throughout the organization and community, resulting in efficient and effective management of infrastructure services. The developed integrated risk and performance evaluation modules design an integrated solution to provide enabling tools to support achievement of the integration of decision-making.

These modules were implemented on the city of Guelph road, watermain, and sewermain sub network. Optimization results showed that the maximum risk reduced / dollar spent was achieved by utilizing one or more corridor rehabilitation option (e.g. road / water / sewer 36%, Road / sewer 23%, Road / water 25%) when the budget is unrestricted. Further sensitivity analysis to the budget constraints showed that the Risk reduced / dollar spent index varies as the budget changes. In conclusion, as the budget increases the number of integrated corridor rehabilitation and risk reduced per dollar spent increases thereby the average network condition improves. Finally, the developed ODM model provides an easy to use informed decision-making approach to assist decision makers with the corridor rehabilitation project selection process.

Asset managers were asked to evaluate the proposed model and approach. The feedback was highly positive as they showed interest and considered adopting the proposed approach in their municipalities. Additionally, various municipal sector employees and asset managers highlighted a number of implementation challenges. Analysis of the workshop results combined with the findings of the in-depth interviews highlighted key lessons learned to implement the developed framework. The result is anticipated to generate a capital corridor rehabilitation program for the city's infrastructure. This framework helps municipalities to evaluate and select feasible optimal assets for integrated corridor rehabilitation.

7.2 Research Contributions

Current research contributed to the state of art of integrated asset management for road, water, and wastewater systems:

- Develop a new methodology to facilitate decision-making process that ensures reliable and effective decisions regarding pursing corridor rehabilitation for road, water and wastewater network
- Develop integrated risk analysis model using K-means and modified Delphi-AHP approach
- Develop integrated performance evaluation model using fuzzy logic and modified Delphi-AHP approach
- Develop a customer driven performance measure index and scale
- Develop economic loss models for replacing any asset earlier than its anticipated useful life
- Develop a decision support system for corridor rehabilitation via *Integer Programming*.
- Develop a prototype tool that implements the developed methodology and recommends an optimal replacement strategy.

7.3 Research Limitations

Current research work has introduced three models in addition to the prototype tool (IDSS). They will assist municipal engineers in coordinating their infrastructure work between road network, water distribution network and wastewater distribution network. In order to deploy any of the developed models in one municipality, the following should be done:

- There should be a good and reliable database system concerning geographic, physical, condition, performance, and financial data. Additionally, the model uses existing deterioration curves, O&M practices, and call centre database.
- Each Asset should be linked to the other assets located within the same road right of way otherwise a GIS spatial analysis, as described in Section 3.2.1 Data Collection and Analysis, should be performed.
- The Delphi – AHP model requires cross functional experts to be involved in defining the contributing factors and establishing the pairwise comparison matrices and reach consensus on the final results. A workshop approach will be used where expert knowledge from operators, maintenance staff, planning, engineers etc. can be used to establish these factors and weights. The more experts involved in building these models, the better results they will get.
- The developed models were limited to available data, further data collection efforts will be required to enhance these developed models.

- In this research, Excel Solver was used to perform the Branch and Bound approach to conduct optimization. Among the limitation of using Excel Solver is the limited number of changing cells, i.e. Excel Solver limits the number of changing cells to 190 cells. Since each project has seven (7) alternatives to be evaluated, only twenty-seven (27) projects can be evaluated at one time.

7.4 Recommendations & Future Work

Since the current research focuses on developing an integrated decision-making model for corridor rehabilitation, further research may enhance the model and extend its use. Recommendations and future research are summarized in the following points:

- *Current study enhancement areas*:
    - Incorporate more economical, operational, environmental and social factors to enhance the developed consequence of failure models (i.e. Impact of surrounding infrastructure such as gas pipelines, cable, trees, etc., water and sewer connections types, and soil types with more specific characteristics). Those factors will add to the strength of the model.
    - A review of segmentation options of road / water / sewer assets is recommended. Various options for segmentation and its implications for risk assessment, performance evaluation, and the physical limits of rehabilitation / replacement should be studied.

- There is a need to improve tracking of level of service provided to customers and link them to asset / technical performance measures. The developed model can be enhanced by collecting more reliable and accurate level of service data for CDPM model and solicitation of customer input into the CDPM model.
- Incorporate the developed tool with web-GIS system to enable easier access to IDSS models by various users.

- *Current study extension areas*:
  - Extending the methodology to include optimization of other assets within the road right of ways (e.g. Bridges, Stormwater, gas pipelines, other utilities, TV cables, electric cables, guard rails, trees, facilities, etc.)
  - Modeling the Benefit-Cost ratio of the various corridor rehabilitation alternatives, and quantifying the social benefits for each alternative.
  - The duplication of data across multiple locations in the organization results in an increased cost to maintain the current information in multiple locations. There is a need to develop a standardized data acquisition tool for municipalities.
  - Additional research is needed, using the proposed methodologies, to examine the impact of corridor rehabilitation on municipal infrastructure budgets, i.e., extending the methodology to optimize fund allocation strategies based on various funding sources (e.g. tax based, rate based, senior level of government's grants, gas tax, etc.).

- Further research to validate the benefits of using the risk based decision-making methodologies obtained under this research by implementing various funding strategy recommendations for both operational and capital spending and measuring the economic loss implications should be pursued.

REFERENCES

AASHTO. (2002). *" Transportation Asset Management Guide", Volume 1.* Washington, DC: American Association of State Highway and Transportation Officials (AASHTO) Publication, RP-TAMG-1-UL.

Al Barqawi, H. (2006). "Condition Rating Models for Underground Infrastructure:Sustainable Water-Mains". MASc. Thesis, Concordia University, Montreal, QC.

Al Barqawi, H., & Zayed, T. (2008). Infrastructure management: Integrated AHP/ANN model to evaluate municipal water mains' performance. *Journal of Infrastructure Systems* , v. 14, no. 4, p. 305.

Al-Aghbar. (2005). "Automated Selection of Trenchless Technology for Rehabilitation of Water Mains". MASc. Thesis, Concordia University, Montreal, QC.

AS/NZS4360. (2004). *"Risk Management Australian/New Zealand Standard"*. Retrieved December 09, 2009, from http://www.cqurire.com/htm/paper/risk/Aust_Standards_4360-2004.pdf

ASCE. (1994). *"Existing Sewer Evaluation & Rehabilitation".* American Society of Civil Engineers (ASCE), Engineering Practice No. 62, USA.

ASCE. (1997). *"Manhole Inspection & Rehabilitation".* American Society of Civil Engineers (ASCE), Engineering Practice No.92, USA.

Bandyopadhyay, T., Dey, P., & Gupta, S. (1997). "A cost-effective maintenance program through risk analysis". *Proceeding AACE International Transactions. 84-89.* Dallas, TX: AACE.

Bhave, P. (2003). *"Optimal Design of Water Distribution Networks".* Nagpur,India: Alpha Science Int'l Ltd., Oxford.

Burns, P. (1990). "Asset Management - A Global View, Building Asset Management (Don't Wait Until 2000)". (pp. 1-15). Australia: Proceeding, Building Science Forum of Australia, Randwick Racecourse, NSW,.

Canadian Construction Association (CCA), Canadian Public Works Association (CPWA), Canadian Society for Civil Engineering (CSCE), Federation of Canadian Municipalities (FCM). (2012). *"Canadian Infrastructure Report Card".* ISBN 978-1-897150-45-0, www.canadainfrastructure.ca.

CERIU. (1997). *"Manuel de standardisation des observations – inspections télévisées de conduites"*. Montréal, Québec: Centre d'expertise et de recherche en infrastructures urbaines (CERIU).

Chughtai, F. (2007). "An Integrated Approach to Sewer Pipeline Condition Assessment". MASc. Thesis, Concordia University, Montreal, QC, Canada.

Chughtai, F., & Zayed, T. (2011). Integrating WRc and CERIU condition assessment models and classification protocols for sewer pipelines. *Journal of Infrastructure Systems, v 17, n 3, p 129-136* .

City of Winnipeg. (2006). *"Annual Financial Report"*. Retrieved June 28, 2009, from City of Winnipeg: http://www.winnipeg.ca/finance/files/2006_annual_report.pdf

Danylo, N., & Lemer, A. (1998). *"Asset Management for the Public Works Manager: Challenges and Strategies, Findings of the APWA Task Force on Asset Management"*. Retrieved december 17, 2009, from American Public Works Association [APWA]: www.apwa.net/documents/resourcecenter/ampaper.rtf

Densham, P. J. (1991). "Spatial decision support systems". *D. J. Maguire, M. S. Goodchild and D. W. Rhind (eds) Geographical information systems: principles and applications, London Longman, pp. 403 - 412.*

Falls, L. C., Haas, R., & Tighe, S. (2006). "Asset Service Index as Integration Mechanism for Civil Infrastructure". *Transportation Research Record: Journal of the Transportation Research Board* , Volume 1957 / 2006, DOI 10.3141/1957-01,PP 1-7.

Fares, H. (2008). "Evaluating the Risk of Water Main Failure Using a Hierarchical Fuzzy Expert System". MASc. Thesis, Concordia University, Montreal, QC.

Fares, H., & Zayed, T. (2009). Risk assessment for water mains using fuzzy approach. *Building a Sustainable Future - Proceedings of the 2009 Construction Research Congress , Seattle, WA, United states*, (pp. 1125-1134).

Fares, H., Shahata, K., Elwakil, E., Eweda, A., Zayed, T., Abdelrahman, M., et al. (2012). "Modelling the performance of pavement marking in cold weather conditions". *J. Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance* , Volume 8, Issue 11.

Ferreira, A., & Duarte, A. (2005). "A GIS-Based Integrated Infrastructure Management System". Proceeding, From Pharaohs to Geoinformatics, FIG Working Week 2005 and GSDI-8, Cairo, Egypt April 16-21.

Ferreira, A., & Flintsch, G. (2004). "Life-Cycle Cost Analysis System for Infrastructure Management". *Proceeding, ICCES04 - International Conference on Computational and Experimental Engineering and Sciences, pp. 1687-1692, Madeira,Portugal.*

FHWA. (1999). *"Asset Management Primer"*. Retrieved December 05, 2009, from Federal Highway Administration, US Department of Transportation: http://www.fhwa.dot.gov/infrastructure/asstmgmt/amprimer.pdf

FHWA. (2002). *"Life-Cycle Cost Analysis Primer"*. Retrieved December 05, 2009, from Federal Highway Administration, US Department of Transportation: http://isddc.dot.gov/OLPFiles/FHWA/010621.pdf

Fishburn, P. C., & Gehrlein, W. V. (1976). "Borda's Rule, Positional Voting, and Condorcet's Simple Majority Principle". *Journal of Public Choice, WINTER 1976, Volume 28, Issue 1, pp 79-88 , pp 79-88.*

Ganeshan, R., Grobler, F., Wang, C., & Coimbatore, V. (2001). "CITYWORK: Application of collaborative technologies for infrastructure management". *J. Computing in Civil Engineering, Vol 15(1), 74-80.*

Grigg, N. S. (1999). "Viewpoint. Infrastructure: Integrated Issue or Tower of Babel?". *Journal of Infrastructure Systems , 5, No. 4, pp. 115-117,.*

Haas, R., Hudson, W., & Zaniewski, J. (1994). "Modern Pavement Management". *J. Krieger Press, Malamar, Florida* .

Halfawy, M. (2008). "Integration of Municipal Infrastructure Asset Management Processes: Challenges and Solutions". *Journal of Computing in Civil Engineering , 22,No. 3, pp. 216-229.*

Halfawy, M. R., Newton, L. A., & Vanier, D. J. (2006). "Review of commercial municipal infrastructure asset management systems". *ITcon , 11* (pg. 211-224).

Halfawy, M. R., Pyzoha, D., & El-Hosseiny, T. (2002). "An Integrated Framework for GIS-Based Civil Infrastructure Management Systems". *Proceeding, Annual Conference of the Canadian Society for Civil Engineering.* Montréal, Québec, Canada: Canadian Society of Civil Engineers.

IIMM. (2006). *"International Infrastructure Management Manual".* New Zealand: New Zealand National Asset Management Steering (NAMS group).

IIMM. (2011). *"International Infrastructure Management Manual".* New Zealand: New Zealand National Asset Management Steering (NAMS group).

InfraGuide. (2003a). *"An Integrated Approach to Assessment and Evaluation of Municipal Road, Sewer and Water Networks".* Canada: InfraGuide best practice,National Guide to Sustainable Municipal Infrastructure.

InfraGuide. (2004). *"Assessment and Evaluation of Storm and Wastewater Collection Systems".* Canada: InfraGuide best practice,National Guide to Sustainable Municipal Infrastructure.

InfraGuide. (2003b). *"Developing a Water Distribution System Renewal Plan".* Canada: InfraGuide best practice,National Guide to Sustainable Municipal Infrastructure.

InfraGuide. (2005). *"Managing Infrastructure Assets".* Canada: InfraGuide best practice, National Guide to Sustainable Municipal Infrastructure.

InfraGuide. (2006). *"Managing Risk".* Canada: InfraGuide best practice, National Guide to Sustainable Municipal Infrastructure.

Islam, T., & Moselhi, O. (2011). "Integrated Asset Management of Roads, Water Mains and Sewers". *Proceedings, Annual Conference - Canadian Society for Civil Engineering, v 1,.* Ottawa, Ontario.

Islam, T., & Moselhi, O. (2012). "Modeling Geospatial Interdependence for Integrated Municipal Infrastructure". *Journal of Infrastructure Systems, v 18, n 2* , p 68-74.

Kleiner, Y., Rajani, B., & Sadiq, R. (2006). "Failure risk management of buried infrastructure using fuzzy-based techniques". *Journal of Water Supply Research and Technology : Aqua , 55(2), 81-94.*

Kleiner, Y., Sadiq, R., & Rajani, B. (2004). "Modeling Failure Risk in Buried Pipes Using Fuzzy Markov Deterioration Process". *Proceeding, Pipeline Engineering and Construction: What's on the Horizon? 1-12.* San Diego, CA: ASCE.

Lashlee, J., Chaney, D., & bearden, K. (2004). *"Pavement Management System".* Retrieved december 14, 2009, from http://www.bgky.org/publicworks/planningdesign/transportation/pdf/2004_pma_report.pdf

Lee, H., & Deighton, R. (1995). "Developing Infrastructure Management Systems for Small Public Agency". *Journal of Infrastructure Systems* , Vol. 1, No. 4, 230-235.

Lemer, A. C. (1998). "Progress Toward Integrated Infrastructure-Asset Management". *NRCC/CPWA Seminar Series "Innovations in Urban Infrastructure"* (pp. 7-24). APWA International Public Works Congress.

MacQueen, J. (1967). "Some methods for classification and analysis of multivariate observations.". *Proceedings of the fifth Berkeley symposium on mathematical statistics and probability, California, USA, 14.*

Marshall, D., Zarghamee, M., Mergalas, B., & Kleiner, Y. (2005). "Tarrant Regional Water District's Risk Management Plan for Prestressed Concrete

Cylinder Pipe". *Proceeding, The Pipeline Division Specialty Conference. 854-861.* Houston, TX: ASCE.

Moglia, M., Burn, S., & Meddings, S. (2006). "Decision support system for water pipeline renewal prioritisation". *ITcon , 11, pp 237-256* (Special Issue Decision Support Systems for Infrastructure Management).

Moore, Andrew. (2001, November 16). Retrieved december 12, 2012, from "K-means and Hierarchical Clustering - Tutorial Slides": http://www.autonlab.org/tutorials/kmeans.html

Moselhi, O. (2005). *"Asset Management For Sustainable Civil Infrastructure".* Retrieved December 07, 2009, from http://www.hbrc.edu.eg/ehbrc/workshop/contents/CMN03.pdf

Muhlbauer, W. (2004). *"Pipeline Risk Management Manual", 3rd ed.* Burlington: Gulf Professional Publishing.

NRC. (2004). *"Assessing Canada's Infrastructure Needs: A Review of Key Studies".* Ottawa, Ontario: Institute for Research in Construction, National Research Council Canada.

NRC. (2001). *"Guidelines for Condition Assessment and Rehabilitation of Large Sewers".* Ottawa, Ontario: Institute for Research in Construction, National Research Council Canada.

Nunoo, C. N.-A. (2001). "Optimization of pavement maintenance and rehabilitation programming using shuffled complex evolution algorithm". doctoral dissertation, Florida International University,United States -Florida. (Publication No. AAT 3006861).

Olson, D. (1996). *"Decision Aids for Selection Problems".* New York: Springer.

OMBI. (2010). Retrieved June 15, 2010, from Ontario Municipal Benchmarking Initiative: http://www.ombi.ca

Pedrycz, W., & Gomide, F. (2007). *"Fuzzy systems engineering: toward human-centric computing".* John Wiley and Sons, Hoboken, N.J, Chapter 4, 67-99.

Pradhan, A., Laefer, D., & Rasdorf, W. (2007). "Infrastructure management information system framework requirements for disasters". *J. Computing in Civil Engineering, vol. 21(2), 90-101* .

PSAB, & CICA. (2007). *Guide to Accounting for and Reporting Tangible Capital Assets.* City of Ottawa: Public Sector Accounting Group of the Canadian Institute of Chartered Accountants (CICA).

Quintero, A., Konaré, D., & Pierre, S. (2003). "Prototyping an Intelligent Decision Support System for Improving Urban Infrastructures Management". *European Journal of Operational Research,* , 162, 654-672.

Raczynski, C. M. (2008). "A Methodology for Comprehensive Strategic Planning and Program Prioritization". doctoral dissertation, Georgia Institute of Technology, Atlanta, Georgia.

Rajani, B., Kleiner, Y., & Sadiq, R. (2006). "Translation of pipe inspection results into condition ratings using the fuzzy synthetic evaluation technique". *Journal of Water Supply Research and Technology: Aqua , 55(1), 11-24*.

Roche, D., Anderson, M., & Kadar, P. (2005). *"New Asset Criticality Model Delivers Improvements to the Management of Risk at City West Water".* City West Water: MWH (mwhglobal.com.au).

Roper, P., & Turner, B. (2008). "Why do we need to take a risk assessment based approach in road safety?". *ARRB Conference 23rd.* Adelaide, Australia: Australian Road Research Board.

Saaty, T. (1980). In *"The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation".* ISBN 0-07-054371-2, McGraw-Hill.

Sadiq, R., Rajani, B., & Kleiner, Y. (2004). "Probabilistic risk analysis of corrosion associated failures in cast iron water mains". *J. Reliability Engineering and System Safety , 86(1), 1-10*.

Shahata. (2008). *"City of Toronto, Technical Memo Identifying Critical Sewers – Risk Model".* toronto: UMA- AECOM Technical Memo #3743-6100.

Shahata, K., & Zayed, T. (2012). "Data Acquisition and Analysis for Water Main Rehabilitation Techniques". *Journal of Structure and Infrastructure Engineering, Taylor & Francis Group* , 8(11): 1054-1066.

Shahata, K., & Zayed, T. (2010). "Integrated decision-support framework for municipal infrastructure asset". *Pipelines 2010: Climbing New Peaks to Infrastructure Reliability - Renew, Rehab, and Reinvest* (pp. v 386, p 1492-1502). Proc. of the Pipelines 2010 Conference,.

Shahata, K., & Zayed, T. (2009). "Integrated Management Approach for Infrastructure Assets". *Proceeding, INFRA 2009 Conference.* (pp. 1-10). Mont-Tremblant,Quebec,Canada: Centre d'expertise et d'études en infrastructures urbaines (CERIU).

Shahata, K., & Zayed, T. (2013). "Simulation-Based Life Cycle Cost (SLCC) Modeling and Maintenance Plan for Water Mains". *Journal of Structure and Infrastructure Engineering, Taylor & Francis Group* , 9(5): 403-415.

Shahata, K., Fares, H., Zayed, T., Abdelrahman, M., Rahman, S., & Al-Barqawi, H. A. (2008). "Practices of Sustainable Pavement Marking in Canada: Synthesis". *Transportation Research Board 87th Annual Meeting.*

Washington DC: Transportation Research Board Annual Meeting 2008 Paper #08-0017.

Shaheen, A. (2005). *"A framework for Integrating Fuzzy Set Theory and Discrete Event Simulation in Construction Engineering".* doctoral dissertation, University of Alberta, Edmonton.

Shen, Y., & Spainhour, L. (2001). "IT: a potential solution for managing the infrastructure life cycle". *Journal of Computing in Civil Enginering , vol. 15(1), 1-2.*

Stantec. (2009). *"Pavement Distress Rating Manual".* Kitchener, ON: Stantec Consulting Ltd.

Stantec. (2005). *"Road needs study".* Township of middlesex centre, ON and City of Guelph, ON: Stantec Consulting Ltd.

Tavana, M., Kennedy, D., Rappaprt, J., & Ugras, Y. (1993). "An AHP-Delphi Group Decision Support System Applied to Conflict Resolution in Hiring Decisions". *Journal of Managemant Systems , 5, No.1, pp 49-74*.

Tersine, R. J., & Riggs, W. E. (1976). "The Delphi Technique: A Long-Range Planning Tool". *Business Horizons , 19, no. 2 pp: 51-56.*

Thompson, P. D. (2012). "Estimating Asset Deterioration and Life Expectancy by Using Levels of Service". *Journal of the Transportation Research Board, No. 2285, Transportation Research Board of the National Academies, Washington,DC* , DOI: 10.3141/2285-03, pp. 19–26.

Transportation Association of Canada. (1999). *"Primer on Highway Asset Management".* Ottawa, ON: Transportation Association of Canada.

Vanier. (2006). "Editorial - Decision Support Systems in Infrastructure Management". *ITcon Vol. 11* , 175.

Vanier, D. (2001). "Why industry needs asset management tools". *Journal of Computing in Civil Engineering , 15* (1, pp. 35-43), Vol. 15, No. , pp. 35-43,.

Vanier, D., & Rahman, S. (2004b). *"A Primer on Municipal Infrastructure Asset Management".* NRC; Report No: B-5123.3.

Vanier, D., & Rahman, S. (2004a). *"Survey on Municipal Infrastructure Assets".* NRC; Report No: B-5123.2.

Wind, Y., & Saaty, T. L. (1980). "Marketing Applications of the Analytic Hierarchy". *J. Management Science , 641-659*.

WRc. (2001). *"Manual of Sewer Condition Classification".* Fourth Edition, UK.

WSDOT. (2004). *"Maintenance Accountability Process Manual".* Olympia, WA: Washington State Department of Transportation.

Yager, R., & Zadeh, L. (1992). *"An introduction to fuzzy logic applications in intelligent systems".* Boston: Kluwer Academic.

Yan, J., & Vairavamoorthy, K. (2003). "Fuzzy Approach for Pipeline Condition Assessment". *Proceeding, New Pipeline Technologies, Security, and Safety. , 467-476.* Baltimore, MD: ASCE.

Zietsman, J., Rilett, L., & Kim, S.-J. (2006). "Transportation corridor decision-making with multi-attribute utility theory". *Int. J. Management and Decision Making , 7, Nos. 2/3, pp.254–266*.

Zimmerman, K. A., & Stivers, M. (2007). *"A Model Guide for Condition Assessment Systems".* National Cooperative Highway Research Program (NCHRP), Project 20-07, Task 206.

APPENDICES

Appendix A

Sample of the Workshop Questions

I. Asset Inventory Questions

1. **Do you have an asset inventory? Is it electronically available or hard copy?**
    - The Water Inventory is electronically available for the watermain system, reservoirs and pumping stations.
    - Pipe network (plus valves and hydrants) are also available on GIS
    - Geodatabase stored on SQL server. Field gathered and office entry.
2. **What information is kept in the inventory? Date received, equipment number, location, value, condition, risk, level of service…what data is kept in inventory?**
    - Provided a sample
3. **How do you define what an Asset is? (e.g. lasts more than a year , worth more than $1000 , ..etc)**
    - Water Geodatabase-originated on paper valve book. The book has location of all water valves/mains
4. **How is your assets segmented? (please provide examples)**
    - Assets are unitized "Node to node"
    - Track items such as T's, reducers, crossers. Watermain connects.
    - Track nodes…not facilities. City infrastructure in geodatabase stops at stations.
5. **Is the same information kept for each asset?**
    - No different information is kept for different types of inventory, i.e. water meters vs watermains, vs valves, hydrants etc
6. **Do you have summary documentation that you think would be useful to expedite development of Integrated Asset Management plans?**
    - Water Financial plans, Quality Management System Operational Plan.
    - Budget document – available online
    - OMBI Benchmarking reports

<u>II. Risk</u>

1. **How do you address risk management in your division?**

- Much is legislation driven. Some risk data is available in documents such as DWQMS documents. DWQMS Operational Plan has been endorsed by Municipal Council and speaks to risk management objectives for the Water Service Area.

2. **What are your risk management priorities? Why?**

- Infrastructure-age, size, quality, proximity to trunk mains/pop density, potable water (maintain), backflow etc.
- Critical customers identified
- DWQMS has identified high priorities.
- On a daily basis, SCADA system is monitored by certified Operators

3. **Are risk factors and/or modeling included in your data? What are these factors?**

- Partially ….In condition assessment and DWQMS,
- Criticality for different users
- If under a bridge/ major road or under a river,
- size of main, and number of customers serviced
- Pipe hydraulic model which is capable of linking into the SCADA system.

4. **How do you model your risk (example triple bottom-line)? Frequency?**

- No triple bottom line. Very occasional special reports

5. **Do you have and can you quantify risk reduction strategies and costs?**

- Annual replacement programs are detailed in the annual Water Operating and Capital Works budgets. Majority of these programs focus on risk reduction.

6. **How are current risk exposures with regard to asset failures identified, evaluated and managed?**

- Risk assessments are undertaken as previously noted with respect to DWQMS
    - Risk mitigation measures are put in place to minimize risk.
- Incidents are investigated after they occur although some minor leaks are found and repaired prior to catastrophic failure.

7. **Can and/or do you compare your risk information to other service areas?**

- No, not comparable to other areas at present.

8. Is risk management assessment routine?

- Enterprise risk assessment for water has been completed and submitted to Municipal Council, as has DWQMS.

<u>III. Levels of Service</u>

1. What are the business activities?

- Water distribution

2. Who are the relevant customers

- General public

3. Have you defined any levels of service? Example (no more than 10 water leaks allowed per year , no pressure drops below 40 psi, no more than 4 hours shut-down). What are they? Are any of your LOS legislated?

- No, but we track various performance measures that can be defined as level of service

4. Do you know what your customers expect for level of service? Are those expectations met? How is this recorded? Do you survey your customers regularly?

- We do not have a specific customer level of service identified
- But generally high expectations – i.e. expect 24/7 perfect conditions – flow, pressure and quality
- When expectations are not met we often get complaints and we record them and act accordingly

5. **What are the factors that affect client / customer level of service? (please discuss the list provided)**

- Currently not modeled

IV. Processes and Decision-Making

1. **What is the process for making integrated asset management decisions in your area?**
2. **How do you decide whether to repair or replace your assets?**

- Water Condition assessment tool—judges pipe condition based on as age, number of breaks, pipe material, presence of lead services, hydraulics and importance factors , but then it gets more complicated-just because a main is old with no/few previous breaks it may be a candidate for relining or other trenchless technologies (eg. HDD).
- Lately, significant concern to watermain replacements associated with lead service replacements.
- Water quality complaints factor into relining decision making process in addition to condition rating – repetitive problem areas (as noted by customer complaints) are given higher priority

3. **Do you integrate water / sewer / road rehabilitation decision? Do you utilize optimization? If yes, what is your optimization objective** (e.g. minimize cost, maximize performance, minimize risk exposure, etc.)**?**

- Water touches all disciplines.
- Water pipe life spans used to be 60 years, now higher (80-100 years). Collect all operation data get input from other divisions. For example if roads are in bad shape, oftentimes will come together and do work.
- Sometimes have to do just water work but generally speaking a combined effort.
- Rate structures are compiled with operation needs
    - General cost-sharing criteria with road replacement component: Combined Water / Sewer project; 50-50 road restoration. (Road 0%)
    - 50/50 split between Water & Local Roads
    - Recognized bad road condition 33-33-33% Road /Water /Sewer
    - Developer-related work: As per Subdivision/Development Agreement

4. **Do you have processes in place, which enable future renewal costs of assets to be predicted, based on asset condition, performance and risk?**

(e.g. Renewal profiles are developed from condition decay curves, system capacity modeling and utilization data, and economic failure predictions and historical costs data

- Use average pipe life and condition to define renewal priorities – financial model is consistent with these forecasts and inflates costs for future year replacement based on updated replacement costs from annual renewal program

5. Do you have any difficulties obtaining information from outside your division?

- Generally not with a few exceptions noted below
- Industrial users—do not share data.
- From private sector some restrictions-some items political decisions.
- Internal departments—generally cooperation in place but lack Electronic or Automatic updates.

Appendix B

Sample of the Interview /Questionnaire

Company Information (optional)

This part is very confidential and not for public use. This part is used only to distinguish between clients' categories (consultant, contractor, public utilities & others)

Municipality / Company :___________________________________

Company's classification ________________________

____

(Municipality , Consultant, Contractor, Client, etc.)

Respondent information

Name:	
Position	
e-mail	
Phone	
Fax	

Thank you so much for your time and cooperation

Researcher:
Khaled Shahata
Research Assistant,
Department of Building, civil and
Environmental Engineering
Concordia University
1455 de Maisonneuve Blvd.West
Montréal Québec, Canada, H3g 1M8
e-mail : kfsfarouk@yahoo.com

A .1 Main Factors that Affect risk assessment for Road , Watermains, and Sewermains:

Please, try to provide us with your evaluation to the factors that contribute to the consequence of failure that affect a typical integrated road segment, watermains, and sewermains. The following list of factors is the list that is suggested by experts from the initial risk assessment workshops. These factors affecting cost of rehabilitation and replacement of R/S/W infrastructure assets were selected based upon four overall Criticality Indices as follows:

- **Economic:** Failures that result in class actions lawsuits, regulatory fines, high repair costs, and loss of revenue. These Economic factors represents the effect of the asset's failure on monetary resources (e.g. repair costs, loss of revenue , etc.)
- **Operational:** Failures that result in functional, operational or maintenance inefficiencies, and could be due to under design or new requirements. These Operational factors represents the effect of the asset's failure on operational ability (e.g. damage to surrounding infrastructure, Loss of production, etc.)
- **Social:** Failures that result in service disruption that would impact customers. These Social factors represents the effect of the asset's failure on society (e.g. loss of service, etc.)
- **Environmental:** Failure of assets resulting in negative impacts to endangered or other species or habitat, to heritage resources, archaeological sites, water courses, aquifers etc. These Environmental factors represents the effect of the asset's failure on the environment (e.g. health impacts, contamination, Pollution, etc.)

If you have any factors that you would like to add or remove, please, feel free to add them in the available blank areas. These factors are:

Main Factor	Sub-Factor (Watermains / sewermains)	Sub-Factor (Road segment)
1. Economic Index		
Economic	Pipe Size (Diameter)	Road Size
Economic	Pipe Depth	Road Width
Economic	Material (Type of Pipe)	Road Material
Economic	Land Use	Land Use
Economic	Accessibility	Road Class
Economic	Road type	
Economic		
Economic		
Economic		
2.0 Operational Index		
Operational	Business Disruption Critical Customer	Business disruption (Critical Customer)

Operational	Hydraulic Impact	Road Width
Operational	Pipe Size (Diameter)	
Operational	Damage to surrounding Assets	Damage to surrounding Assets
Operational	Sewermain Blockages	
Operational		
3.0 Environmental Index		
Environmental	Water body proximity	Water body proximity
Environmental	Sensitive Area	Sensitive Area
Environmental	Average Daily Traffic	Average Daily Traffic
Environmental	Type of Soil	Type of Soil
Environmental		
Environmental		
Environmental		
4.0 Social Index		
Social	No Diversion	No Diversion
Social	Land Use	Land Use
Social	Transit Route	Transit Route
Social	Average Daily Traffic (Road Class)	Average Daily Traffic (Road Class)
Social		
Social		
Social		
Social		

A.1.1 Pair-Wise Comparison

Please, try to make a comparison between each factor and the other factors based on your evaluation to the importance of this factor over the other. In other words, compare the importance of each factor against each of the other factors individually. This importance is evaluated regarding its effect on impact of failure (consequence of failure) . The importance of each factor and sub factor are based on a 1-9 scale with the following interpretations.

which **9** = Absolute importance of one over compared one

7 = Very strongly

5 = Strongly

3 = Moderately

1 = Equally important

Measured on an integer-valued 1 - 9 scale as mentioned above.

In this part, you are kindly requested to do pair wise comparison for the importance of parameter. Comparing each two sub factors in a pair wise comparison, you are kindly asked identify the weight of each sub factor with respect to another.

Consequence of Failure (General Parameters)											
Criterion (X)	Degree of Importance or Preference									Criterion (Y)	Remarks
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
Economical										Operational	
										Environmental	
										Social	

Economic Parameters Priorities

Table 1-A (pair wise comparison for economic parameters)

Consequence of Failure (watermains- Economic Parameters)											
Criterion (X)	Degree of Importance or Preference									Criterion (Y)	Remarks
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
Pipe Size (Diameter)										Pipe Depth	
										Material (Type of Pipe)	
										Land Use	
										Accessibility	
										Road type	

Table 1-B (pair wise comparison for Economic parameters)

Consequence of Failure (Sewermains- Economic Parameters)											
Criterion (X)	Degree of Importance or Preference									Criterion (Y)	Remarks
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	**(1) Equal**	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
Pipe Size (Diameter)										Pipe Depth	
										Material (Type of Pipe)	
										Land Use	
										Accessibility	
										Road type	

Table 1-C (pair wise comparison for Economic parameters)

Consequence of Failure (Road - Economic Parameters)											
Criterion (X)	Degree of Importance or Preference									Criterion (Y)	Remarks
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	**(1) Equal**	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
Road Size (e.g. 2 lanes-one way)										Road Width	
										Road Material	
										Land Use	
										Road Class	

Operational Parameters Priorities

Table 2-A (pair wise comparison for Operational parameters)

Consequence of Failure (watermains- Operational Parameters)												
Criterion (X)	**Degree of Importance or Preference**										**Criterion (Y)**	**Remarks**
	(9) Absolute	**(7) Very Strong**	**(5) Strong**	**(3) Moderate**	**(1) Equal**	**(3) Moderate**	**(5) Strong**	**(7) Very Strong**	**(9) Absolute**		
Business Disruption Critical Customer										Hydraulic Impact	
										Pipe Size (Diameter)	
										Damage to surrounding Assets	

Table 2-B (pair wise comparison for Operational parameters)

Consequence of Failure (Sewermains- Operational Parameters)												
Criterion (X)	**Degree of Importance or Preference**										**Criterion (Y)**	**Remarks**
	(9) Absolute	**(7) Very Strong**	**(5) Strong**	**(3) Moderate**	**(1) Equal**	**(3) Moderate**	**(5) Strong**	**(7) Very Strong**	**(9) Absolute**		
Business Disruption Critical Customer										Hydraulic Impact	
										Pipe Size (Diameter)	
										Damage to surrounding Assets	
										Sewermain Blockages	

Table 2-C (pair wise comparison for Operational parameters)

Consequence of Failure (Road - Operational Parameters)											
Criterion (X)	Degree of Importance or Preference									Criterion (Y)	Remarks
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	**(1) Equal**	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
Business Disruption Critical Customer										Road Width	
										Damage to surrounding Assets	

Environmental Parameters Priorities

Table 3-A (pair wise comparison for Environmental parameters)

Consequence of Failure (watermains- Environmental Parameters)											
Criterion (X)	Degree of Importance or Preference									Criterion (Y)	Remarks
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	**(1) Equal**	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
Water body proximity										Sensitive Area	
										Average Daily Traffic	
										Type of Soil	

Table 3-B (pair wise comparison for Environmental parameters)

Consequence of Failure (Sewermains- Environmental Parameters)											
Criterion (X)	Degree of Importance or Preference									Criterion (Y)	Remarks
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
Water body proximity										Sensitive Area	
										Average Daily Traffic	
										Type of Soil	

Table 3-C (pair wise comparison for Environmental parameters)

Consequence of Failure (Road - Environmental Parameters)											
Criterion (X)	Degree of Importance or Preference									Criterion (Y)	Remarks
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
Water body proximity										Sensitive Area	
										Average Daily Traffic	
										Type of Soil	

Social Parameters Priorities

Table 4-A (pair wise comparison for Social parameters)

Consequence of Failure (watermains- Social Parameters)											
Criterion (X)	Degree of Importance or Preference									Criterion (Y)	Remarks
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
No Diversion										Land Use	
										Transit Route	
										Average Daily Traffic (Road Class)	

Table 4-B (pair wise comparison for Social parameters)

Consequence of Failure (Sewermains- Social Parameters)											
Criterion (X)	Degree of Importance or Preference									Criterion (Y)	Remarks
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
No Diversion No Diversion										Land Use	
										Transit Route	
										Average Daily Traffic (Road Class)	
										Land Use	

Table 4-C (pair wise comparison for Social parameters)

Consequence of Failure (Road - Social Parameters)											
Criterion (X)	Degree of Importance or Preference									Criterion (Y)	Remarks
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
No Diversion										Land Use	
										Transit Route	
										Average Daily Traffic (Road Class)	

A2. Scaling Parameters

In order to be able to deploy the resultant weight of each factor, scale should be assigned to each parameter so we would be able to predict the consequence of failure for each asset. The following section describes the suggested scale by other expertise, scaled (1 to 5), ("1"represent the lowest scale value or insignificant impact of failure, and "5" represent the highest scale value or catastrophic impact of failure). Please feel free to modify it according to your experience so we would be able to develop a reliable model. Please refer to the table below for the definition of each scale point.

Table A2 -1 Watermains Consequence of Failure Variables Scores

Factors	Score	Factors	Score
1. Economic Parameters			
1.1 *Pipe Size (Diameter)*		***1.4 Land Use***	
Less or equal 300 mm	1	Agricultural	1
300 to 450 mm	2	Park / open space	2
450 to 750 mm	3	Residential	3
750 to 1200 mm	4	Commercial	4
Greater or equal 1200mm	5	Institutional	5
		Industrial	5
1.2 Pipe Depth		**1.5 Accessibility**	
Less or equal 2.0 m	1	Good	1
2.0 to 3.0 m	2	Marginal	3
3.0 to 3.5 m	3	Low	5
3.5 to 4.0 m	4		
Greater or equal 4.0 m	5		
1.3 Material (Type of Pipe)		**1.6 Road type**	
Galvanized Steel (GALV)	5	Local	1
Steel (ST)	4	Arterial	3
Pitted Cast Iron (CIp)	3	Expressway / hwy	5
Spun Cast Iron (CIs)	3	Collector	2
Ductile iron (DI)	4	University	4
Copper (Cu)	5		
Concrete Pressure Pipe (CPP)	5		
Asbestos Cement (AC),	3		
Poly Vinyl Chloride (PVC)	1		
High Density Poly Ethylene (HDPE)	2		
Ductile Iron Hyprotech (DIHY)	2		
2.0 Operational Parameters			

Factors	Score	Factors	Score
2.1 Business Disruption Critical Customer Low High (major users, hospitals, health clinics)	 1 5	**2.3 *Pipe Size (Diameter)*** Less or equal 300 mm 300 to 450 mm 450 to 750 mm 750 to 1200 mm Greater or equal 1200mm	 1 2 3 4 5
2.2 Hydraulic Impact Pass Fail	 1 5	**2.4 *Damage to surrounding Assets*** Low Medium High	 1 3 5
3.0 Environmental Parameters			
3.1 Water body proximity Greater or equal 200 m away 101 to 200 m 51 to 100 m 5 to 50 m Less or equal 5 m	 1 2 3 4 5	**3.3 *Average Daily Traffic (Road Class)*** Low Moderate Heavy	 1 3 5
3.2 Sensitive Area No Yes	 1 5	***3.4 Type of Soil*** Non-Aggressive Moderate Aggressive Highly aggressive	 1 2 3 5
4.0 Social Parameters			
4.1 No Diversion No Yes	 1 5	**4.3 Transit Route** No Yes	 1 5
4.2 Land Use Agricultural Park / open space Residential Commercial Institutional Industrial	 1 2 3 4 5 5	**4.4 *Average Daily Traffic (Road Class)*** Low Moderate Heavy	 1 3 5

Table A2-2 Sewermains Consequence of Failure Variables Scores

Factors	Score	Factors	Score
1. Economic Parameters			
1.1 Pipe Size (Diameter)		***1.4 Land Use***	
Less or equal 300 mm	1	Agricultural	1
300 to 450 mm	2	Park / open space	2
450 to 750 mm	3	Residential	3
750 to 1200 mm	4	Commercial	4
Greater or equal 1200mm	5	Institutional	5
		Industrial	5
1.2 Pipe Depth		**1.5 Accessibility**	
Less or equal 2.0 m	1	Good	1
2.0 to 3.0 m	2	Marginal	3
3.0 to 3.5 m	3	Low	5
3.5 to 4.0 m	4		
Greater or equal 4.0 m	5		
1.3 Material (Type of Pipe)		**1.6 Road type**	
Poly Vinyl Chloride (PVC)	1	Local	1
Clay (CT, VC)	2	Collector	2
Asbestos Cement (AC, TRAN)	3	Arterial	3
Corrugated steel pipe (CSP)	3	Custom (e.g. University)	4
Metalic (STL, DI, CI)	4	Expressway / hwy	5
Concrete (RC)	5		
Concrete (HYPRES)	5		
2.0 Operational Parameters			
2.1 Business Disruption Critical Customer		***2.4 Damage to surrounding Assets***	
Low	1	Low	1
High (major users, hospitals, health clinics)	5	Medium	3
		High	5
2.2 Hydraulic Impact		***2.5 Sewermain Blockages***	
d/D ≤0.5	1	Low	1
0.5 – 0.65	2	Medium	3
0.65 – 0.75	3	High	5
0.75 – 0.85	4		
d/D ≥0.85	5		
2.3 Pipe Size (Diameter)			
Less or equal 300 mm	1		
300 to 450 mm	2		
450 to 750 mm	3		
750 to 1200 mm	4		
Greater or equal 1200mm	5		
3.0 Environmental Parameters			
3.1 Water body proximity		***3.3 Average Daily Traffic (Road Class)***	
Greater or equal 200 m away	1		
101 to 200 m	2	Low	1
51 to 100 m	3	Moderate	3
5 to 50 m	4	Heavy	5
Less or equal 5 m	5		

Factors	Score	Factors	Score
3.2 Sensitive Area No Yes	 1 5	***3.4 Type of Soil*** Non-Aggressive Moderate Aggressive Highly aggressive	 1 2 3 5
4.0 Social Parameters			
4.1 No Diversion No Yes	 1 5	**4.3 Transit Route** No Yes	 1 5
4.2 Land Use Agricultural Park / open space Residential Commercial Institutional Industrial	 1 2 3 4 5 5	**4.4** ***Average Daily Traffic (Road Class)*** Low Moderate Heavy	 1 3 5

Table A2-3 Roads Consequence of Failure Variables Scores

Factors	Score	Factors	Score
1. Economic Parameters			
1.1 *Road Size (#lanes)*		***1.4 Land Use***	
Local	1	Agricultural	1
Collector - 2 lane	1	Park / open space	2
Collector - 3 lane	2	Residential	3
Arterial - 2 lane	3	Commercial	4
Arterial - 3 lane	3	Institutional	5
Arterial - 4 lane	4	Industrial	5
Arterial - 5 lane	4		
Arterial - 6 lane	5		
Expressway - 4 lane	5		
1.2 Road width		**1.5 Road type**	
Less or equal 8.0 m	1	Local	1
8.0 to 12.0 m	2	Collector	2
12.0 to 16.0 m	3	Arterial	3
16.0 to 20.0 m	4	Custom (e.g. University)	4
Greater or equal 20.0 m	5	Expressway / hwy	5
1.3 Road Material			
GST Granular	1		
Low Class Bituminous	2		
High Class Bituminous	3		
Asphalt over Concrete	4		
Concrete	5		
2.0 Operational Parameters			
2.1 Business Disruption Critical Customer		**2.3 *Damage to surrounding Assets***	
Low	1	Low	1
High (major users, hospitals, health clinics)	5	Medium	3
		High	5
2.2 Road width			
Less or equal 8.0 m	1		
8.0 to 12.0 m	2		
12.0 to 16.0 m	3		
16.0 to 20.0 m	4		
Greater or equal 20.0 m	5		
3.0 Environmental Parameters			
3.1 Water body proximity		**3.3 *Average Daily Traffic (Road Class)***	
Greater or equal 200 m away	1		
101 to 200 m	2	Low	1
51 to 100 m	3	Moderate	3
5 to 50 m	4	Heavy	5
Less or equal 5 m	5		
3.2 Sensitive Area		***3.4 Type of Soil***	
No	1	Non-Aggressive	1
Yes	5	Moderate	2
		Aggressive	3
		Highly aggressive	5

Factors	Score	Factors	Score
4.0 Social Parameters			
4.1 No Diversion		**4.3 Transit Route**	
No	1	No	1
Yes	5	Yes	5
4.2 Land Use		***4.4 Average Daily Traffic (Road Class)***	
Agricultural	1	Low	1
Park / open space	2	Moderate	3
Residential	3	Heavy	5
Commercial	4		
Institutional	5		
Industrial	5		

Appendix C

Sample Database attributes

Data type	Attribute description
Basic Asset/Component Information	• Asset ID (Identification number/serial number) • Asset Class or type • asset sub-type/asset usage • Linkage between assets (parent and child relationships) • Component description and quantity (e.g. size, construction type, etc.) • Location (e.g. street address, city, county, postal code, geocoding (latitude & longitude) • Status of asset (e.g. in use, vacant, or surplus to needs) • Date and method of acquisition (e.g. purchase, construction, donation) • Year Installed/ Year Assumed • Date and nature of major rehabilitation • Expected Useful Life (ESL) / Remaining Service Life (RSL)
Financial Information	• Unit costs • Total replacement cost • Replacement cost method • Historical cost • Amortization method and rate • Accumulated amortization • Net book value • Annual amortization expense • Put-in-service date • Date of financial accounting values • Link to Budget documents • Link to projected investment plan
Condition Information	• Condition rating • Factors included in condition assessment (or link to reports) • Date and method of last condition assessment • Deterioration profile / curves (or link to reports)
Performance Record	• Performance rating • Factors included in performance evaluation (or link to reports) • Levels of Service Index (customer / technical) • Date and method of last performance assessment
Risk Information	• Risk index • Factors included in risk assessment (or link to reports) • Date and method of last risk assessment
Maintenance Record	• Work order number • Link to maintenance history • Date and method of last inspection/maintenance activity